

Fluidized-Bed Combustion Technology Overview

GCA Corp.
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Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

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FLUIDIZED BED COMBUSTION
TECHNOLOGY OVERVIEW

Final Report

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SECTION 1.0

SUMMARY

Fluidized bed combustion (FBC) of coal is rapidly becoming commercially feasible. While a great deal of progress has been made towards commercialization of this technology, there are still a number of key technical issues which must be resolved before a significant market penetration can occur. This is the first in a planned series of annual technology overview reports which summarizes previous work, identifies significant trends, and assesses the key technical issues.

The previous year, 1978, can best be described as a building year for FBC technology. The industrial atmospheric fluidized bed (AFB) demonstration plants are all at the design or construction stage. The major pressurized fluidized bed (PFB) pilot plants at Curtiss-Wright and Grimethorpe are in design or construction. The utility AFB pilot plant at Rivesville was shut down for a major part of the year due to a coal strike and a fire in the air preheater. The conceptual AFB utility plant designs are finished. Some small scale, operational data was generated from the Electric Power Research Institute (EPRI) facility, Curtiss-Wright technology rig, and others.

Several significant developments took place last year. These include:

- The fire in the Rivesville air preheater has placed the use of electrostatic precipitators for FBC in serious doubt. This, coupled with tighter particulate emission standards recently announced by the U.S. Environmental Protection Agency (EPA), may eliminate electrostatic precipitators from serious consideration in the near future.
- The utility AFBC demonstration program is being transferred to the government owned Tennessee Valley Authority. The nation's largest utility also appears to be a natural place for this effort.

- Licensing of British FBC technology in the U.S. is well underway, with the Johnston Boiler Company and the Riley Stoker Corporation obtaining licenses.
- Industrial FBC usage is beginning to increase, primarily due to efforts by the U.S. Department of Energy (DOE), the State of Ohio, and others. The risk is still too great for many industries, but cost sharing by DOE may offset this factor.
- PFB technology is making progress with the Grimethorpe facility nearing completion. Also, there is a DOE program opportunity notice for hot gas cleanup.
- Experience at Rivesville and Babcock & Wilcox confirms that coal and limestone feeding is still a major problem.

SECTION 2.0

INTRODUCTION

Development of fluidized bed combustion of coal has been under way since the early 1960s in this country and in England. The original intent of the development program was to reduce the size of a coal-fired boiler to make it competitive with oil- and gas-fired boilers which could burn fuel in a much smaller space. In England, the concept was advanced by reducing the combustion space through pressurization and by coupling the combustor with a gas turbine in an attempt to improve the thermal efficiency of electrical generation.

With the advent of the Clean Air Act in 1970 and the requirement of flue gas desulfurization (FGD) on boilers using high sulfur coals, many operators turned to a low sulfur coal rather than assume the costs and problems associated with FGD systems. Great interest was generated in the FBC, since it was known that much of the sulfur in the coal could be captured by burning it in a fluidized bed of limestone. This interest was deepened by the energy crisis and the realization that coal must supply a larger portion of our energy needs in the future. The FBC process was viewed as a potential alternative to FGD. In addition to controlling sulfur emissions, it was found that FBC also has the potential of lowering NO_x emissions.

In a fluidized bed, a fluid, normally a gas, is forced upward through a bed of granular or powdered solid material. As the gas flow rate is increased, a point is reached where the weight of the solid material is offset by the drag of the gas passing through the bed. At this gas velocity, the bed is said to be fluidized, since the bed now behaves like a fluid, i.e., it conforms to the shape of the container, maintains a generally level surface. The particles move freely as long as the gas velocity is maintained.

In a coal combustion fluidized system, limestone (CaCO_3) or dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$) is the bed material. At elevated temperatures, limestone calcines (or releases CO_2) to form lime (CaO). This lime reacts with sulfur dioxide released in the coal combustion to form calcium sulfate (CaSO_4). Dolomite is typically used in pressurized systems and limestone in atmospheric systems. Dolomite's performance is better at pressure which is thought to be due to the stability of CaCO_3 at pressure. While the calcined MgCO_3 (MgO) does not react directly, it seems to aid in the direct reaction of CaCO_3 .

Coal is burned in an atmospheric fluidized bed (AFB) combustor at $1,500 - 1,600^\circ\text{F}$, with temperatures slightly higher for pressurized fluidized beds (PFB). The temperature is established primarily by the optimum temperature for sulfur capture. In general, the sulfur capture improves with temperature up to this range and then drops sharply. Several theories have been developed to attempt to explain this drop, but none have been completely confirmed.

While a great deal of progress has been made toward commercialization of this technology, there are still a number of key technical issues which must be resolved before a significant market penetration can occur. It is the purpose of this technology overview report to summarize the work that has been done to date, identify significant trends, discuss the present status of the technology, and assess the key technical issues facing fluidized bed combustion.

This report was prepared under a subcontract between the GCA/Technology Division and Gilbert Associates, Inc. GCA is a prime support contractor to EPA for their fluidized bed combustion program.

SECTION 3.0

ATMOSPHERIC FLUIDIZED BED COMBUSTION (AFBC)

3.1 BACKGROUND

Atmospheric fluidized bed is being developed for both industrial and utility applications. The use of fluidized bed combustion technology in industrial boilers is rapidly becoming commercially feasible. Presently, there are no large industrial fluid bed boilers in operation, however, several small units have been sold and two large demonstration units are under construction. The rate of commercialization for the larger industrial fluid bed boilers will depend on the performance of the demonstration units and the impact of industrial boilers emission standards which are now being formulated.

Early work on fluidized bed coal combustion in this country was directed toward producing a rail shippable industrial boiler with a greater capacity than available. Pope, Evans and Robbins (PER) began developing fluidized bed combustion in 1965 using this approach. In 1968, their emphasis was redirected to developing a fluidized bed boiler to improve air pollution control. At this time, the U.S. Office of Coal Research (OCR) decided to fund the design, construction, and operation of a pilot plant at Alexandria, Virginia. This facility, called the Fluidized-bed Boiler Module (FBM), had a bed size of 1 1/2 ft x 6 ft and was the largest operating facility in the U.S. for many years.

The development of utility units will follow the development of industrial units. Utility units have to be much larger, and the utilities require more certainty in the efficiency and overall costs of equipment purchases, since their costs are regulated by state commissions. Initially, it had been thought that atmospheric units would be in utility service first, with pressurized units to follow.

However, with the American Electric Power Company initiative in PFBC and the TVA initiative in AFBC, the introduction of both types of units with utility service could come in parallel. The atmospheric fluidized bed utility plants will use conventional Rankine cycles, while pressurized fluidized bed units will use a combined gas turbine topping cycle with a steam bottoming cycle.

3.2 INDUSTRIAL AFBC

Pope, Evans and Robbins began developing an industrial fluidized bed boiler in this country in 1965. Since the initial design was to produce a rail-shippable package boiler, the boiler had tubes in the walls. This resulted in a long, slender bed in order to have enough wall surface in contact with the fluidized bed. Their pilot plant in Alexandria, Va. produced the initial data for much of the U.S. FBC program.

3.2.1 Renfrew (Babcock & Wilcox, Ltd.)

The development of fluidized bed combustion in England began in 1961 at the Central Electric Generating Board and in 1963 at the British Coal Utilization Research Association. This work led to the conversion of an existing water-tube boiler to fluidized bed firing. This boiler supplied steam to Babcock and Wilcox Limited's Renfrew Works. The stoker, on what was originally a Babcock cross-type boiler, was replaced with a 10 ft x 10 ft fluidized bed.² This unit is capable of firing coal, oil, or natural gas. For coal firing, either dense-phase or dilute-phase injection can be used.

The fluidized bed retrofit started operations in June 1975 firing coal crushed to 95 percent less than 1/8 in. Initially the unit operated at a fluidizing velocity of four ft/sec and about 23,000 lb/hr of steam. Modifications were made to operate the boiler at eight ft/sec, which doubled the steam generating capacity.

Much of the information on this boiler is proprietary, however, as shown on Figure 1, it features underbed injection of coal, recycle of collected carryover material, a single hair-pin tube pass in the bed, and pump assisted circulation. Steam conditions are 400 psig and 520°F.³ A range of coals have been fired including an Irish coal containing 60 percent ash.

Encouraged by the Renfrew results, Riley Stoker Corporation has entered into a licensing agreement with Babcock & Wilcox, Ltd. to market and fabricate fluidized bed boilers in the U.S. The FBC technology will be applied to the design of industrial, institutional, and municipal boilers in the range of 50,000 to 500,000 lb/hr steam category. The first installation of the Babcock/Riley Stoker fluidized bed unit will be a retrofit of a boiler at the Central Ohio Psychiatric Hospital in Columbus. It will produce 60,000 lb/hr steam, burn Ohio coal with 4.45 percent sulfur, and meet EPA emission requirements. Babcock/Riley have also proposed a large scale test facility at the Picaway Plant of the Columbus & Southern Ohio Electric Company. This would be a 355,000 lb/hr boiler to demonstrate fluid bed boiler operation under utility conditions.

3.2.2 The Department of Energy (DOE) Industrial Demonstration Program

In keeping with the objectives of the National Energy Policy to increase the use of coal and reduce dependence on imported oil and natural gas in the United States, DOE has assumed the risk in the early stages of developing fluidized bed combustion technology. The rationale for the DOE decision is:

- An environmentally acceptable and cost effective method of coal combustion must be developed to permit industry to convert from oil and natural gas to coal. An economic analysis of coal fired industrial boilers of 400,000 lb/hr steam capacity indicates that

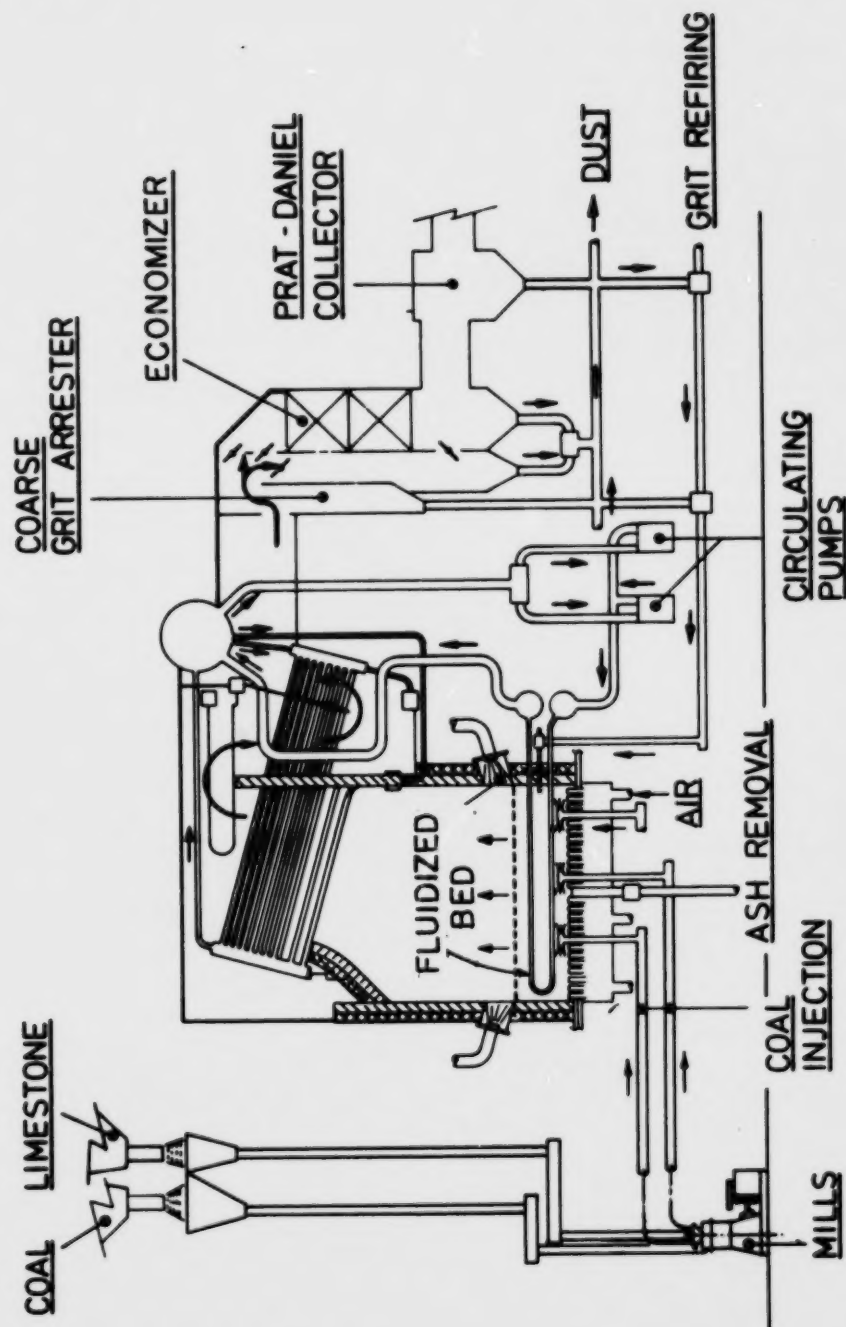


FIGURE 1
RETROFIT FLUIDIZED BED BOILER
RENFREW, SCOTLAND

atmospheric fluidized bed combustion (AFBC), when compared to conventional steam generation with flue gas desulfurization (FGD), will generate steam based on the current emission requirements for about \$1.00 less per 1,000 lbs of steam. When proposed New Source Performance Standard (NSPS) are applied, AFBC could be \$2.00 cheaper per 1,000 lbs of steam generated.

- For industrial applications, AFBC is an alternative to using scarce and interruptible natural gas or oil. Due to the reluctance of industry to use a new coal based technology, Federal involvement in industrial AFBC programs is required.
- Industry will not purchase an AFBC unit until it is judged reliable, operable, economic, and efficient. Demonstrations of these features can be accomplished only with large scale operating equipment.

Based on the above, an industrial AFBC demonstration program was initiated by DOE. The objective of the program is to design, build, operate, test, and demonstrate prototype boilers and heaters to establish the practicality of burning high sulfur coals and other fuels for industrial applications. Another objective is to obtain sufficient experimental data from prototype operations to enable the industry to design, construct, and operate selected prototypes in full plant sized installations.

Three areas of industrial applications are being investigated:

- Saturated Steam Boiler - Capable of producing steam of the quality and quantity suitable for process and space heating requirements of industrial and institutional facilities.

- Superheated Steam Generator - Capable of producing steam of the quality and quantity for both cogeneration (via back pressure turbines) and industrial process and heating requirements.
- Indirect Fired Process Heater - For heating process liquids or gases.

Five contractors were selected to design, construct, and test industrial boilers/heaters using AFBC as shown in Table 1. These are discussed in detail in Sections 3.1.4 through 3.1.8.

TABLE 1

U.S. DOE INDUSTRIAL FBC CONTRACTORS

<u>Contractors</u>	<u>Steam (heat) Rate</u>	<u>Coal Rate - ton/hr</u>
Georgetown University and Fluidized Combustion Co.	100,000 lb/hr Saturated steam	5.0
Combustion Engineering/ Great Lakes Naval Training Center	50,000 lb/hr Superheated steam	2.5
Battelle Memorial Institute/ Fluidized Combustion Co.	25,000 lb/hr Saturated steam	1.0
Fluidyne/Owatoona Tool Co. Minnesota	Hot air to 780°F 28 x 10 ⁶ Btu/hr	1.5
Exxon Research & Engineering Co., N.J.	Petroleum crude heater 15 x 10 ⁶ Btu/hr	0.75

In 1978, DOE initiated the anthracite waste coal combustion program using fluidized bed technology. The waste material resulting from the mining and cleaning of anthracite coal in northeastern Pennsylvania has a substantial fuel value, which can be recovered in a fluidized bed boiler/combustor in an environmentally acceptable manner. The goal for fiscal year 1978 was to select contractors to develop and demonstrate prototype equipment. Table 2 is a list of the selected contractors and the steam and coal firing rates. This program is discussed in Section 3.2.9.

TABLE 2
SELECTED WASTE ANTHRACITE COAL FBC CONTRACTORS

<u>Contractor</u>	<u>Steam Rate-lb/hr</u>	<u>Coal Rate-ton/hr</u>
Wilkes-Barre, Pa/ Fluidized Combustion Co.	100,000	5
Shamokin Area Industrial Corporation, Pa/Curtiss- Wright/Door-Oliver	20,000	1
Towanda, Pa/Fluidyne	20,000	1

Very recently, DOE issued a Program Opportunity Notice (PON) seeking additional participation in industrial FBC demonstrations. This PON resulted from a task force report that stated that the risk in FBC technology is still too great for near term industrial application. DOE offers 20 to 40 percent of the boiler plant costs to offset this risk. Five major energy use areas were identified as preferred users. These use areas are the food industry, the pulp and paper industry, the chemical industry, the petroleum industry, and the primary metals industry. These industries are all heavy users of steam. Proposals are due to DOE by the end of August 1979.

3.2.3 Georgetown University (Fluidized Combustion Company)

In 1976, the Energy Research and Development Administration (ERDA) selected Georgetown University as prime contractor and the Georgetown campus as the site for a coal fired industrial/institutional atmospheric fluidized bed boiler. The contract provides for the development and construction of an addition to the existing central heating plant. The new 100,000 lb/hr AFB boiler will supply the university's steam distribution system to meet their increasing load requirements.

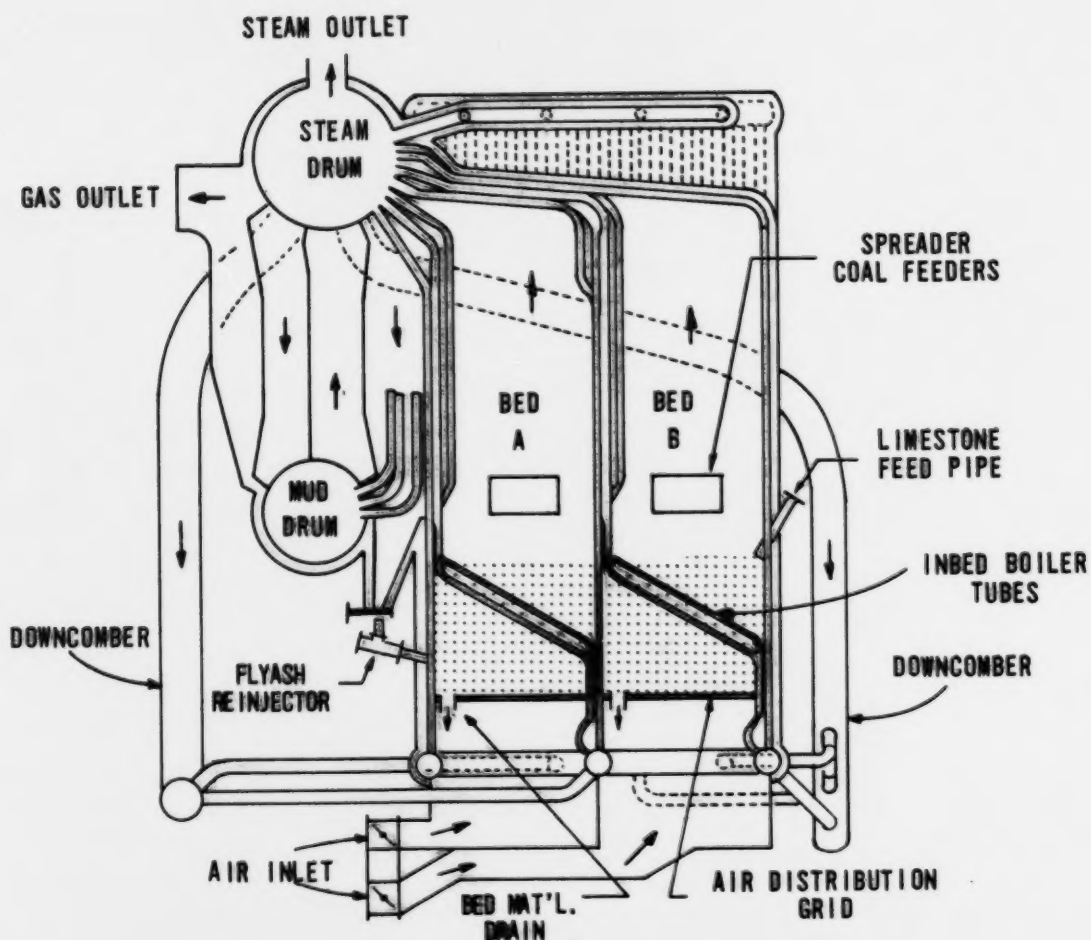
Georgetown University and its support contractors were awarded a contract for a 675 psig/100,000 lb/hr boiler. The contract provides for the engineering, design, construction, testing, operation, and evaluation of an atmospheric fluidized bed boiler using high sulfur coal.

Georgetown University is teamed with Fluidized Combustion Company (FCC) as its subcontractor. FCC is a joint, wholly owned subsidiary of Pope, Evans and Robbins, Inc., an engineering consulting firm, and the Foster Wheeler Corporation, a supplier of equipment to the steam power industry. Georgetown University is the overall program manager and will be responsible for plant operation, fuel, and manpower as well as environmental assessment studies, scientific testing, and fluidized bed performance evaluation.

Georgetown University's 2.2 million ft² of buildings in Washington, DC are heated and cooled by steam and chilled water from a central heating plant. The fluidized bed boiler will be tied to the existing steam distribution system by a pressure reducing station.

The fluidized bed boiler features two beds as shown on Figure 2. Bed A, adjacent to the boiler bank, is the primary bed. The primary bed is always ignited first and maintained whenever the unit is

FIGURE 2
 FLUIDIZED BED STEAM GENERATOR
 GEORGETOWN UNIVERSITY
 100,000 LBS/HR. 675 PSIG DESIGN PRESSURE
 SATURATED STEAM



operating. Bed B does not operate without Bed A in service. This dual bed approach improves flexibility and turndown capability while enhancing boiler reliability.

The fluidized bed design uses a fluidizing velocity of eight ft/sec and reinjects fines into the bed. Complete shop assembly and shipment to the job site on a fully assembled basis can be made whenever the location permits barge shipment.

The Georgetown FBB uses a natural circulation steam loop which is featured with most industrial boilers since it simplifies operation and improves reliability.

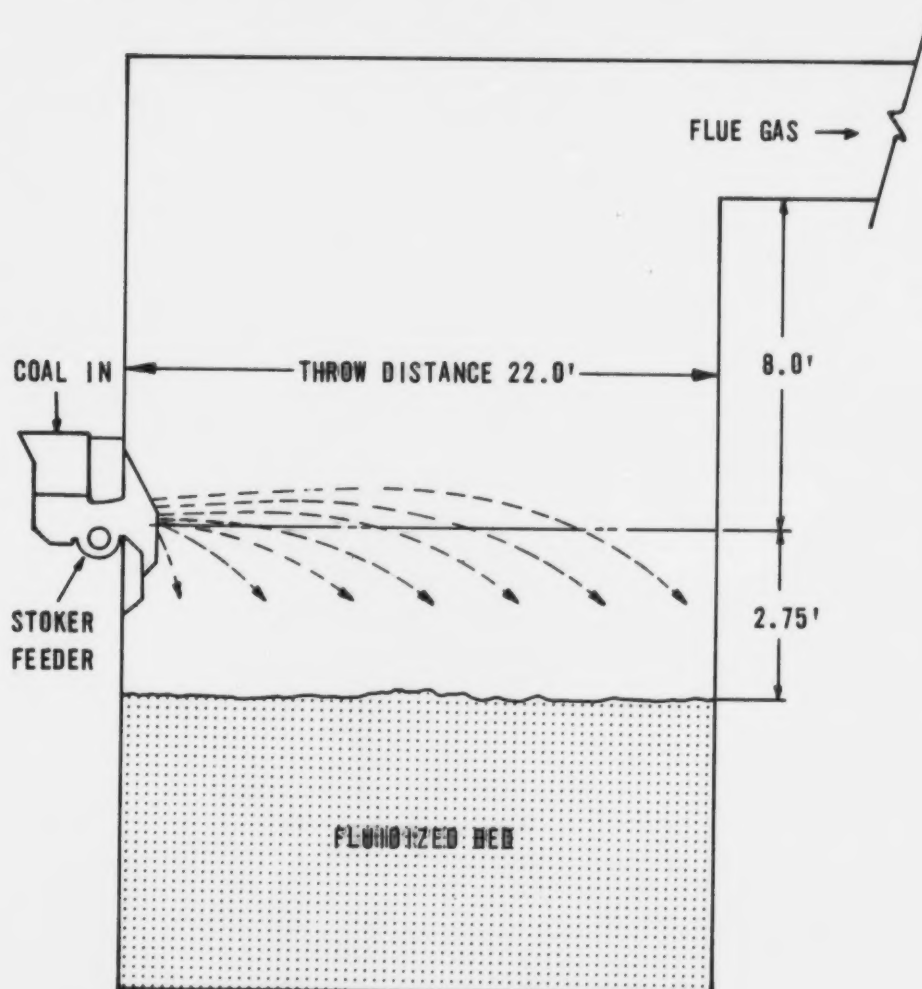
A unique design feature of this fluidized bed boiler is the use of spreader stoker coal feeders which throw the coal across the top of the bed (Figure 3). This feeder greatly decreases the number of coal feed points required and simplifies the coal feeding system. However, its application to a fluidized bed combustion system has not been demonstrated. Initial operation of the boiler will be with double screened coal sized 1-1/4 in. x 1/4 in. Double screened coal is more expensive than conventional stoker coal which has a size range of 1-1/4 in. x 0.

3.2.4 Great Lakes Naval Training Center (Combustion Engineering)

This project will develop and demonstrate a shop assembled water wall, fluidized bed boiler that can be shipped by rail. This package boiler would also feature a natural circulation water/ steam loop.

The program is divided into two phases. In Phase I, a two-dimensional cold model (2 in. x 23 in.) and a three-dimensional model (29.5 in. x 25 in.) were designed. The two-dimensional model was used to perform screening tests on air distributor plates and determine bubble

FIGURE 3
COAL THROW PATTERN FROM A
SPREADER STOKER FEEDER



growth properties. The results showed that bubbles are limited in size up to a seven ft/sec design velocity range. The three-dimensional model was then used to evaluate the effect of various tube configurations. These tests showed that the spacing of the tubes in the bed did not substantially affect the pressure drop or the minimum fluidizing velocity. Also, the inclined tubes provided a damping effect on freeboard splash at higher velocities.

A subscale test unit was designed and constructed in Phase I. This unit is a 3 ft x 3 ft fluidized bed module designed to deliver 2,300 lb/hr of steam at 365 psig and 560°F while burning coal in a limestone bed at 284 lb/hr.

The subscale unit (SSU), a modular section of the demonstration boiler, has been built and operated. This facility includes the basic systems required of a full scale plant. Approximately 300 lb of coal mixed with 100 lb of limestone is pneumatically fed into the 5.6 ft² bed through a single fuel line. An inlet duct burner raises the inlet air temperature to 550° for start-up. A cyclone char collector recycles char to the bed to control the carbon loss.

The objectives of the SSU are as follows:

- Thermal - Demonstrate natural circulation capabilities; determine heat transfer coefficient; transient response to primary input step changes; and temperature behavior of the fluid bed.
- Combustion - Determine the combustion parameters such as volatile release and freeboard burning; carbon burnup cell performance oxygen distribution; and coal ignition temperature.
- Environmental - Determine the of SO_x, NO_x, and particulate emissions; evaluate the performance of the fluid bed and auxiliary gas handling equipment.

Phase II consists of the detailed design, construction, and testing of a full size (8 ft x 17 ft) fluidized bed package boiler as a demonstration plant. This unit has a capacity of 50,000 lb/hr steam at 365 psig and 560°F while burning 5,000 lb/hr of coal.

The demonstration unit is a three-drum design arranged with the boiler banks in an "A" configuration. This is similar to the Combustion Engineering "A" type industrial boiler and is shown in Figure 4. It provides a symmetrical, rigid structure ideal for shipment and shop assembly. The overall dimensions (13 ft L x 19 ft W x 18 ft H) are within rail shippable limits. By increasing the boiler length, the shop assembled concept could be rail shippable for up to 200,000 lb/hr steam capacities.

The superheater surface is completely immersed in the fluidized bed. The tubes are supported by the water cooled rear wall and by attachments on the bed tubes. A steam cooled spacer tube assures proper alignment of the superheater during operation.

Air for fluidization is introduced through a bottom air plenum which is divided into eight equal compartments or zones. The unit uses a punched plate with 0.1 in. diameter holes as a distributor plate. The number of active bed zones in operation is the primary means of regulating the capacity of the unit. Illinois No. 6 coal containing 3.5 percent sulfur will be burned. A calcium-to-sulphur (Ca/S) mole ratio of four is expected to meet the SO_x emission requirements.

3.2.5 Battelle Memorial Institute (Fluidized Combustion Co.)

Battelle has been developing the multisolids fluid bed combustion (MS-FBC) concept for several years. The MS-FBC can be considered a hybrid of an entrained transport system superimposed on a dense phase fluidized bed combustion process. Figure 5 illustrates this concept.

FIGURE 4
GREAT LAKES NAVAL FLUIDIZED BED
DEMONSTRATION BOILER, 50,000 LBS/HR.

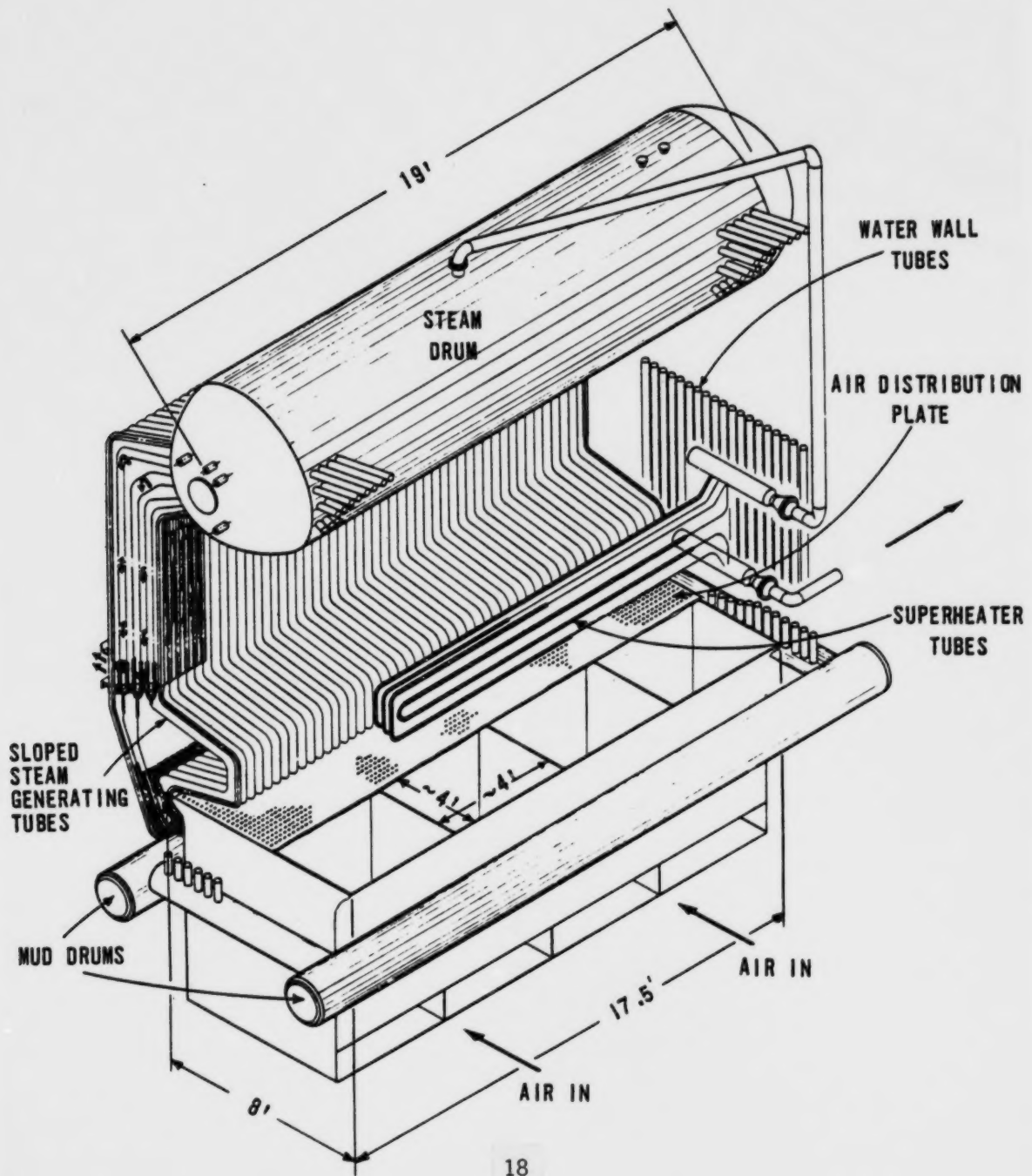
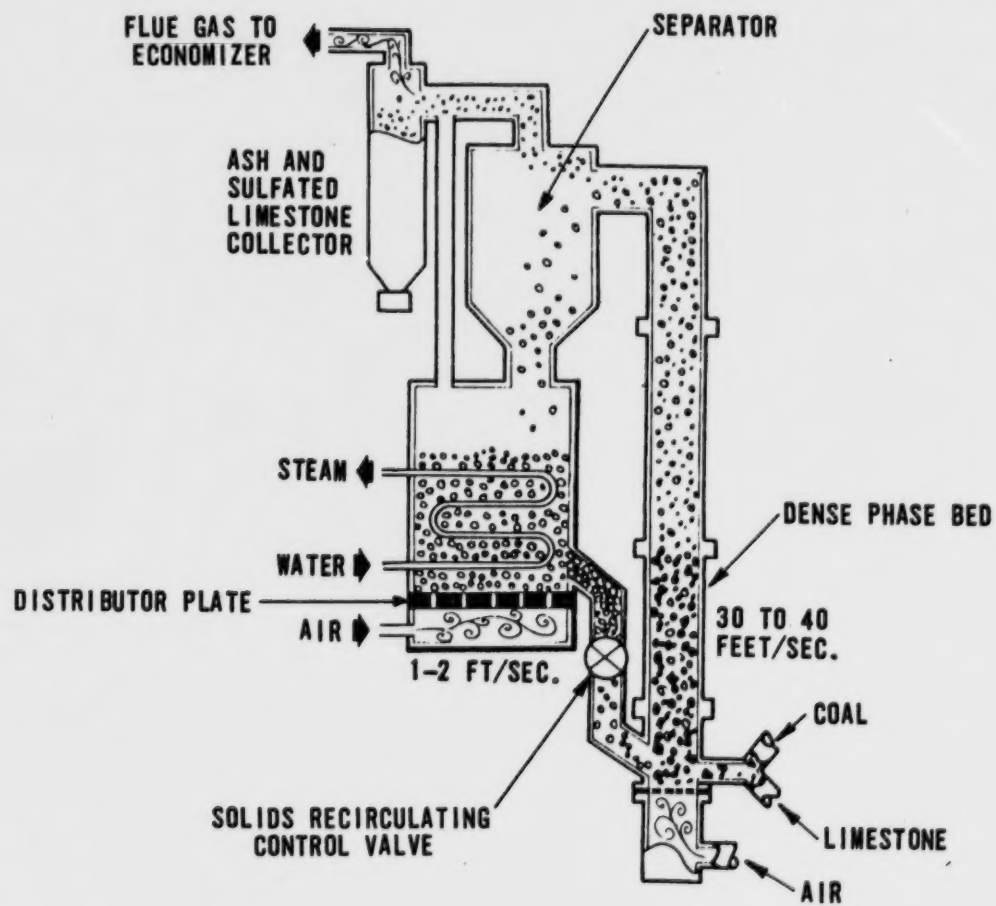


FIGURE 5
 BATTELLE MULTI-SOLIDS FLUIDIZED BED
 COMBUSTION (MS-FBC) CONCEPT



During operation, MS-FBC has two distinct zones in the combustor column. The bottom zone is the dense bed phase or region, where a heavy bed material is fluidized and retained. Above the dense phase is the entrained bed region, consisting of fine particles of sand or heavy bed material. The entrained bed material is carried upward by the gas stream into a gas-solid separator. The material is recycled into the combustor.

Air at a velocity of 30 to 40 ft/sec fluidizes the bed and combusts the coal. Finely ground limestone captures the sulfur. The dense phase in the bed is a high specific gravity material such as specularite (iron ore). The sulfated limestone and ash are blown out of the dense phase and collected downstream.

The MS-FBC system can be operated with an integral or external boiler. In an integral boiler system, the vertical heat exchanger tubes are immersed in the entrained bed. With an external boiler, the steam tubes are immersed in a separate fluidized bed operated at a fluidizing velocity of one to two ft/sec. The hot entrained bed material at 1,600 to 1,750°F is separated from the exhaust gases and drops into the external boiler section. The hot gases leaving the separator and external boiler are cleaned of ash and sulfated limestone before moving to a convective heat exchanger/economizer, where the gas is cooled to a reasonable stack temperature. About one-third of the steam is produced in the economizer and the remainder in the external boiler.

The technical feasibility of the MS-FBC has been demonstrated in a six in. diameter, 20 ft long bench scale combustion unit at Battelle. Limestone of less than 100 micron particle size and crushed coal of less than 1/4 in. was used in the combustor. The unit operated at a temperature of 1,600 to 1,750°F at atmospheric pressure. A combustion efficiency of 96 percent was obtained. The six in. diameter unit has been operated at loads ranging from 100 percent to about 20 percent with no apparent difficulties.

The MS-FBC can meet the environmental constraints on SO_x and NO_x emissions. A smaller amount of dry solids is produced for disposal due to low calcium-to-sulphur requirements. The unit has excellent load following and turndown capabilities as well as restart and shutdown characteristics. It can use a variety of fuels and limestone absorbents.

Additional engineering and developmental advantages claimed for the unit are applicability to retrofit existing boilers, greatly reduced corrosion and erosion of steam tubes, natural circulation of water, and fewer scale-up problems. The unit is claimed to have low operating and capital cost due to the low limestone requirements, low amount of solid waste, and compactness.

The current DOE contract calls for a two phase scale-up of the process over a six year period, which includes three years of operation of a demonstration plant. The subscale experimental unit system (SSEUS), which represents a tenfold scale-up of the six in. benchscale unit, is now in operation. It is designed to produce 4,000 lb/hr of steam with a coal feed rate of 400 lb/hr. The full scale demonstration unit is intended to produce 25,000 lb/hr of steam at a coal feed rate of 2,500 lb/hr. The program will be completed by the last quarter of 1982.

3.2.6 Owatoona Tool Company (Fluidyne Engineering Corp.)

The objective of this project is to design, construct, and operate an atmospheric fluid bed combustion, combination air/hot water heater and distribution system. The system will supply heated, low pressure air and hot water to meet the space heating and process needs of the Owatoona Tool Company and will handle the load fluctuations in this 265,000 ft² plant and office complex. Potential applications for hot air in this plant include paint drying and curing, metal preheating and reheating operations, and heat source for fluid bed, spray, and rotary dryers.

A process schematic for the air and water system is shown in Figure 6. The full scale demonstration unit will include two rectangular FBC each 5 ft x 11 ft. Low pressure air will be heated to 800°F in the in-bed heat exchanger. This air, after being mixed with the recirculated air stream will be supplied at 250-500°F. The hot air will be used directly in space heating and make-up air heaters and indirectly to heat water to 250°F for additional space heating, domestic hot water heating, paint cleaning and stripping baths, and for various metal processes.

The total system heat load varies from 1×10^6 Btu/hr to 28×10^6 Btu/hr depending on season and time of day. The system is being designed for a -23°F day, thus providing a severe test for the ability of the FBC system to respond rapidly and efficiently to variable and peak load requirements.

Design support studies were conducted in three test rigs: (1) a square 24 in. plexiglass, cold flow model; (2) a square 18 in. combustor; and (3) a 40 in. x 64 in. combustor, which is one-third of the full size unit.

The cold flow testing will optimize the heat exchanger surface in the bed. The square 18 in. combustor will confirm the in-bed heat exchanger performance and evaluate the effect of feed location, bed temperature, and particulate recycling on combustion efficiency and sulfur absorption. Bed temperature and feed location had little effect on the combustion efficiency of the unit; however, recycling of particulates improved the combustion efficiency to 95 percent or better with three different fuels: Iowa coal, Tennessee coal and petroleum coke. Illinois limestone and Owatonna dolomite were used in the experiments. The SO₂ emissions from the unit were less than 1.2 lb/10⁶ Btu.

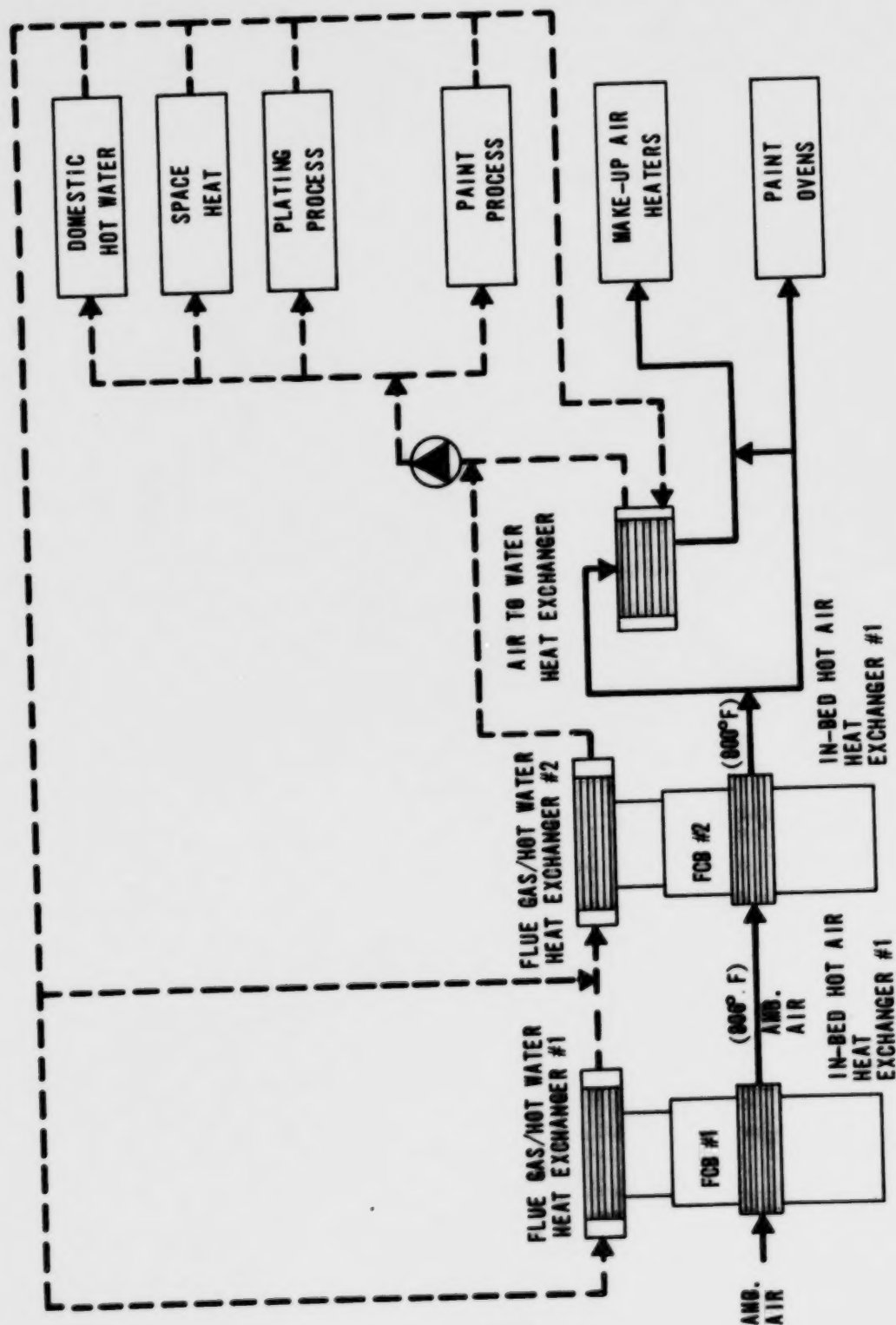


FIGURE 6
AIR AND WATER PROCESS SCHEMATIC
FOR THE OWATONNA TOOL COMPANY PROJECT

A 500 hour test run was conducted with the 40 in. x 64 in. combustor to demonstrate equipment performance over a longer period of continuous operation. The test included long term fixed and variable load operation. Combustion efficiencies at various loads ranged from 93 to 95 percent. The sorbent feed rate ranged from 0.3 to 0.45 lb per lb of coal to meet EPA emission standards for SO_2 . The EPA NO_x standard ($0.7 \text{ lb}/10^6 \text{ Btu}$) was also achieved at all operating levels. The coal was not dried, and the moisture content varied from two to 11 percent.

3.2.7 Exxon Research & Engineering

The goal of the Exxon program is to conduct a technical and economic assessment of the FBC concept for application to refinery and chemical plant process heaters. Two principal areas of technology being addressed in the program are the effects of tube size and the potential for hydrocarbon coking.

In direct fired process heaters, tube diameters are larger than conventional boiler tube diameters. A typical crude oil heater may have a number of four to eight inch diameter tubes in the heat transfer zones as compared to the one to two inch diameter tubes used in typical steam generators. The effect of the larger tubes and tube bundles on fluidization and heat transfer characteristics will be determined in this program.

The parameters affecting hydrocarbon coking at temperatures higher than 600°F will be determined by calculating the local heat transfer coefficient around the heat exchanger tubes. The rate of coke laydown is affected by the temperature of the hydrocarbon film on the inside wall of the tube, which is affected by the inside film coefficient and heat transfer rate to the unit.

The effect of coking and tube size is being evaluated through the design, fabrication, and operation of three separate laboratory test units: a two-dimensional flow visualization unit, a process stream coking unit, and a high temperature heat flux unit.

The two-dimensional flow visualization study which defined the range of acceptable tube bundle configurations suitable for commercial process heater application has been completed. The process stream coking test has also been completed. Preliminary data analysis indicates that the coking rate is not a function of the process film temperature but is a strong function of the mass velocity through the unit. The design and construction of the heat flux test unit has been completed, and it is scheduled to begin testing in the second quarter of 1979.

3.2.8 Johnston Boiler Company

The Johnston Boiler Company of Ferrysburg, Michigan, under a technology and patent license with Combustion Systems Ltd., U.K., has developed a fluidized bed combustion steam generator for industrial and commercial process steam and heating applications. This design is a fire tube packaged boiler offered in size ranges from 2,500 to 50,000 lb/hr of steam with full performance guarantees. The Johnston boiler is claimed to be capable of efficient and environmentally acceptable combustion of coal, fuel oil, and natural gas, either separately or in combination.

Johnston uses a balanced draft, tapered, fluidized bed design with a water cooled combustion chamber and watertube bed divider as shown on Figure 7. The hot gas leaving the bed is passed through the fire tube heating surface, and the unburned carbon particles are recycled to the bed for complete combustion. The limestone bed is operated at a temperature of 1,500°F. Mechanical dust collectors are used to meet the particulate emission requirements. The combustor system is a multicell fluidized bed combustor designed as a complete, factory

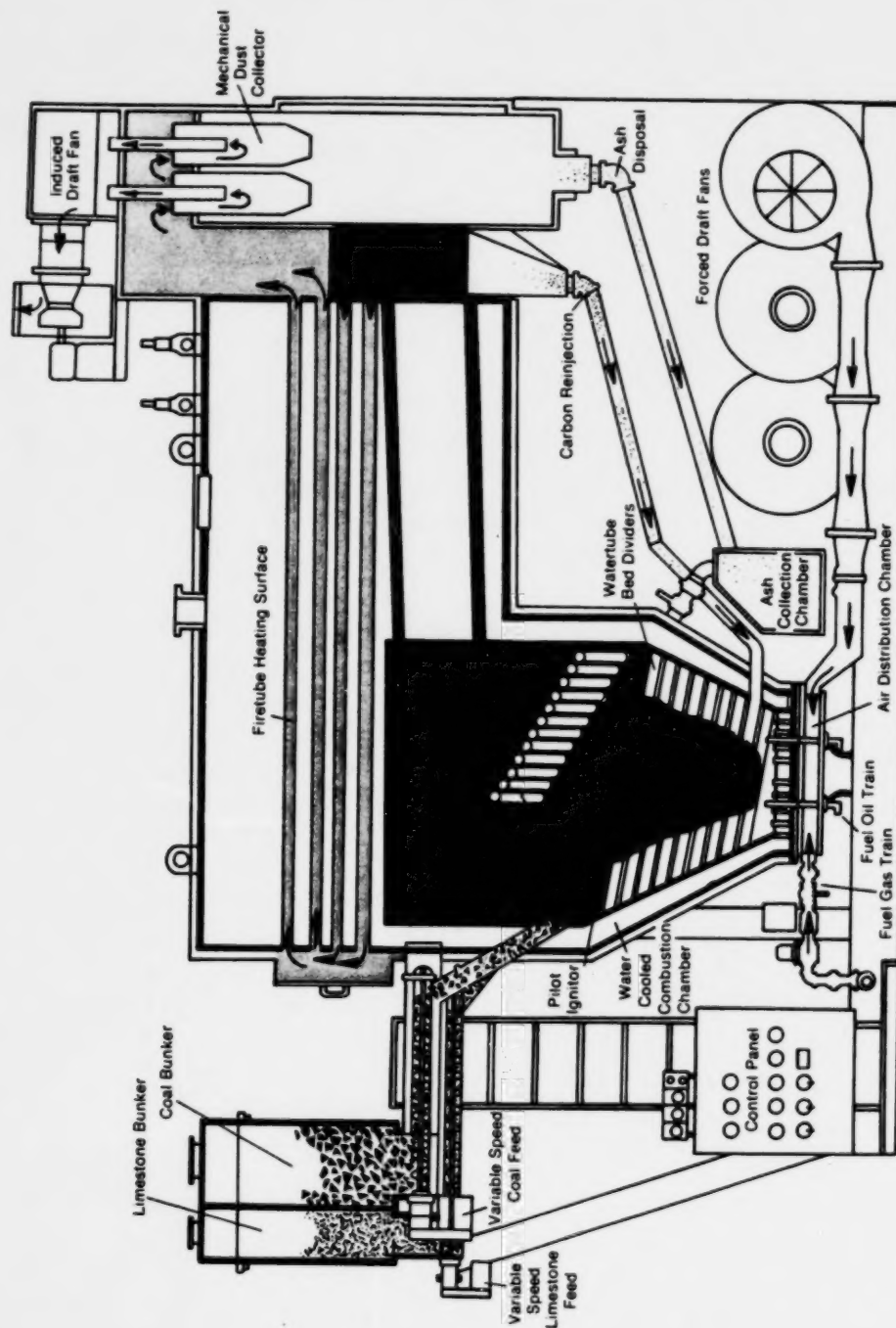


FIGURE 7
JOHNSTON FLUIDIZED BED
FIRE TUBE PACKAGED
BOILER

assembled package system for automatic firing. The multicell design provides a turndown of 6:1.

The fuel-to-steam efficiency is 76, 83, and 80 percent with coal, oil, and gas, respectively. Each unit is capable of achieving a minimum combustion efficiency in excess of 90 percent, and the unit is claimed to be capable of meeting the Federal emission standards for stationary boilers.

Johnston will supply units with capacities ranging from 2,500 to 50,000 lb/hr of steam. The design pressure is 160 psi and 250 psi for water and steam, respectively.

3.2.9 Anthracite Applications

DOE has initiated three programs for the development and demonstration of waste anthracite coal combustion technology using FBC. The three projects being funded in this area are listed in Table 2. Anthracite culm is the discarded material from anthracite mining operations. It can contain from 25 percent to 45 percent coal and possess a heating value of approximately 3,000 to 6,000 Btu per lb. The value of anthracite culm as a fuel is local to the northeastern Pennsylvania anthracite region. The most economic sources are culm banks within five miles of the user's site, where the fuel cost will be the transportation cost of about \$1.50 per ton. With anthracite coal selling at \$30 to \$50 per ton plus transportation charges, culm could be economically shipped over a distances of possibly 50 miles. Economic incentives for the commercial implementation of the technology are strong for this northeastern Pennsylvania region.

The overall objective of the program is to establish the technical, economic, and environmental feasibility of burning anthracite culm in a FBC for generating process steam and to design, build, and test,

prototype boilers. These boiler demonstrations will establish the commercial practicality of burning anthracite culm and obtain sufficient data from prototype operations to enable scale-up for commercial applications.

3.2.10 Mustad & Son A.S., Norway

A district heating system, based on the direct combustion of solid, liquid, and gaseous fluids in fluidized bed furnaces with controlled heat transfer and water as a heat distribution medium, has been designed by the Norwegian engineering firm of Mustad & Son. This plant was commissioned in Enköping, Sweden in 1978 and will be undergoing demonstration runs through 1980. Multiple fuels, including coal, milled peat, wood chips, and high sulfur residual oils, will be burned in the unit. The unit has a heat generation capacity of 25 MWt and will supply heat for 16,000 dwellings.

The unit is operated at a temperature of 1,500°F with limestone as the sulfur absorbent. The flue gases leaving the bed are at a temperature of 1760°F. The system has provision for the introduction of secondary air above the bed in order to complete the combustion.

Mustad has extended its application of the fluidized bed technology for the combustion of organic waste substances, which can be fed into the system in liquid or solid form. They have been successful in burning oil sludge, paint and varnish waste, polyethylene, PVC, polypropylene, PCB-rich oil, waste from pharmaceutical industries, sulfite, lye, and domestic waste. The hot flue gases are passed over the heat exchanger and cleaned in bag filters. The particulate from the bag filter, in the case of pigment combustion, contains oxides of heavy metals, which are disposed of directly to a garbage dump for domestic wastes due to the low solubility of the heavy metal oxides.

3.2.11 Stone Platt Fluidfire, Ltd., England

Prof. Douglass Elliott of the University of Aston showed in 1971 that stable combustion of propane can be achieved in a shallow (less than six inches) fluid bed of alumina particles. The heat transfer coefficient to the tubes in a shallow fluidized bed is much higher than a conventional fluidized bed. This discovery lead to the founding of Fluidfire, Ltd., in the United Kingdom.

Fluidfire, Ltd. has used the shallow bed principle for the design of heat treating and wire patenting machines which have been sold throughout the world. Recently, the shallow fluid bed was used in an industrial waste heat boiler on the back end of a 12,000 hp Sulzer diesel engine running on heavy fuel oil. This unit was installed in a 40,000 ton Norwegian tanker.

The hot gases discharged from the diesel at a temperature of 590 to 610°F are passed through distributor plate with a two in. deep shallow bed, in which extended surface tubing is arranged in a single panel. The unit is operated at a fluidizing velocity of six ft/sec with a bed of 500 micron alumina particles. The heat transfer coefficient to the extended surface is 50 to 60 Btu/hr-ft²-°F.

The unit is divided into three trays each 9 ft x 12 ft, one above the other, and the gas is ducted to the three trays in parallel. Each bed consists of three panels of extended surface evaporating tubes, which deliver steam at 200 psig. The unit is 18 ft high and weighs approximately 30 tons.

Fluidfire is investigating the design for a liquid petroleum gas tanker, which would produce superheated steam for a turbine generating one MWe. It is also considering the design of a five MWe marine unit for cogeneration.

3.3 UTILITY AFBC

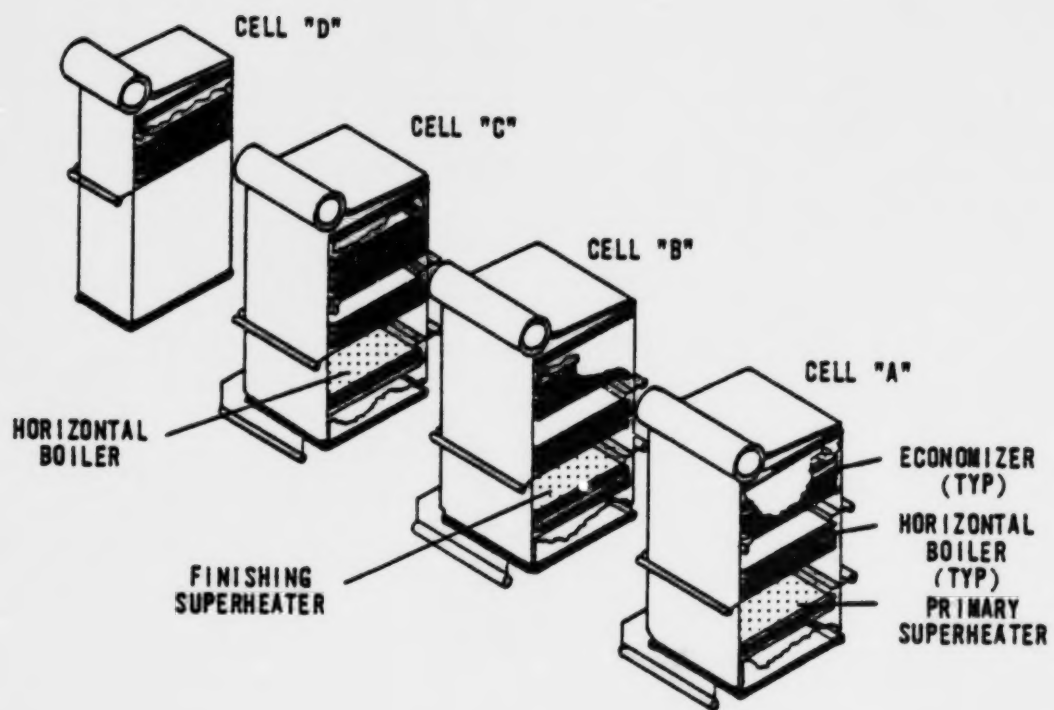
3.3.1 Rivesville Demonstration Unit

In October 1972, the Office of Coal Research (OCR) contracted with Pope, Evans & Robbins (PER) to design, construct, and operate a 30 MWe experimental fluidized bed boiler. This unit is located at the Rivesville Power Station of the Monongahela Power Company which is a part of the Allegheny Power System.⁵

In order to minimize construction costs and maximize the demonstration value of the unit, it was decided to install the unit in an existing plant. It was believed that shared use of existing coal and ash handling facilities, boiler water treatment equipment, and the delivery of steam to an available turbine generator set would be more cost effective. The boiler erection began in September 1974 and the construction was completed in February 1977.

The Rivesville boiler, built by Foster Wheeler, is a water cooled furnace which is 12 ft wide by 37 ft long by 20 ft high. It is a modular design with four internal cells. The primary cells (A, B and C) burn coal, which is premixed with limestone. The fourth cell (D) completes combustion of the unburned carbon in the fly ash, which has been collected in the cyclone separators and electrostatic precipitators. An exploded view of the boiler is shown in Figure 8. The primary cell temperature is 1,500°F, while the carbon burnup cell (CBC), is operated at a temperature of 2,000°F. The unit is designed to produce 300,000 lb/hr of steam at 1,350 psig and 925°F.

FIGURE 8
THE RIVESVILLE FLUIDIZED BED BOILER
BUILT BY FOSTER WHEELER



The Rivesville Multicell Fluidized Bed Boiler (MFB) began operation in December 1976. The unit was oil fired using the start-up burners. Initial start-up, debugging, and first operation took place in 1977. In this period, the boiler was operated at nameplate conditions, and this was the first fluidized bed boiler to generate electricity.

The Rivesville unit has since been fired with three percent sulfur coal with Sewickley limestone, screened to 1/8 in. by 16 mesh, as the bed material.

Significant early problems included:

- Coal handling - The original coal handling system was redesigned when the sulfur limit in delivered coal for Monongahela Power changed from three percent to less than two percent.
- Coal drying - The coal drier was designed to use preheated air from the combustion air duct as the drying medium and to vent this air to the electrostatic precipitator. This arrangement was deemed unsafe, and a new supplier of double screened dry coal was found.
- Bed light-off - Difficulty was encountered in initially firing the carbon burn-up bed. It was found that the CBC bed temperature could be raised to coal ignition temperature by reversing the combustion gas flow through the cell and grid plate while maintaining a slumped bed and 100 percent fuel oil firing rate.
- Coal feeding - Coal pluggage in the rotary feeder and in the fuel needles was a major problem in establishing successful coal firing. Coal feeding problems were aggravated by a high percentage of fines (less than 20 mesh) and high moisture content (greater than three percent). A high percentage of fines in the coal causes partial fluidization in the coal feed pipe when air

leaks from the lower rotary feeder and flows upward through the pipe. With a lower percentage of fines, this air continues up through the pipe and is vented with little or no harm other than loss of air.

- Grid plate distortion - The grid plate suffered damage under the fuel feed nozzles. This was caused by the coal impinging on the grid plate and local overheating and expansion problems.
- Water supply - The quantity of water required to sustain three cell operation while venting to the atmosphere exceeded expectations. This problem was partially solved by renting portable demineralizers.

Several significant positive results were obtained during the early testing period. Methods were developed to light off large beds and start up adjacent beds by the transfer of hot material.

The maximum steam generation of 304,000 lb/hr was obtained on four cells. Conclusions were that the MFB would be capable of producing higher steam flows with deeper beds. This conclusion was reinforced when the heat transfer coefficient was found to be higher than the original estimate.

The quick response of the fluidized bed boiler shows potential for following load swings without encountering upsets. A positive aspect of MFB operation is its ability for restart without heating the beds if operation is reestablished within four hours following a fuel trip. Hot restart can take place in less than one hour.

The Rivesville unit was not operational in the first quarter of 1978 due to a strike by United Mine Workers. In April 1978, the Rivesville unit initiated shake-down operation modifications and improvements. In

May, D Cell operated continuously for 200 hr, and comprehensive performance tests were begun. The D Cell performance tests were completed in June 1978.⁷

The Rivesville MFB was operational during July and early August 1978, with significant achievements including comprehensive performance and emission testing, continuous operation of the CBC Cell for 220 hr, generation of electric power for 95 hr, and continuous operation of C Cell for 95 hr.

In August, the MFB boiler plant sustained serious auxiliary equipment damage as a result of a fire in the regenerative rotary air preheater. The first visual indication of fire was flames being emitted from the stack. Poor electrostatic precipitator performance had been observed for several days prior to the fire. The stack plum was extremely heavy and had an unusual yellow tinge. All systems were operating normally with the exception of the automatic control of the ID fan dampers which had been placed in manual.

Personnel involved in unit operation or fire fighting underwent an extensive interviewing process in the days after the fire. The product of these interviews and the visual inspections and materials testing was a consensus view of the cause of the fire. The fire caused extensive damage to the air preheater, the I.D. fans, the electrostatic precipitators, and the ducting.

In addition to repairing the fire damage, additional tasks have been scheduled for improving the operating capabilities of the boiler system. Some of the more important items are: 1) fire protection system, including an air preheater diluge system; 2) improvement of the combustion air damper sealing; 3) incorporating design changes to the electrostatic precipitation to obtain increased collection efficiency; and 4) modifications to the instrument and control systems.

To improve the particulate collection efficiencies at the fluidized bed boiler, several actions are being taken. First, the EPA will conduct a series of tests to establish performance standards for particulate control. They will test a baghouse filter, an electrostatic precipitator, and a wet scrubber. The units and their auxiliaries are mobile trailer mounted and will be located approximately 60 feet west of the Monongahela Power Company building which houses the MFB unit. Also, a small unit (baghouse) supplied by the Buell Emission Control Division of Envirotec will be installed at the Alexandria Laboratory.

From September to December 1978, repair, reconstruction, and plant improvement activities continued.

Support testing at Alexandria during this period was on a drilled bolt air distributor design proposed for the Rivesville MFB. This distributor consists of a 1/4 in. thick carbon steel plate each containing 2,784 5/16 in. x 18 stainless steel bolts on 0.724 in. centers. Each bolt projects 1-3/4 in. above the plate and is drilled out to 7/64 in. (0.1094). This results in approximately two percent open area. During operation, the 1-3/4 in. space fills with bed material. Since this material is not fluidized, it will form a stagnant zone insulating the grid plate from the fluidized portion of the bed. A total of 94 hours of hot testing of this design were completed with approximately 15 temperature cycles. A drilled bolt air distributor has been installed in the carbon burnup cell at Rivesville.

3.3.2 Morgantown Component Test and Integration Unit (CTIU)

The atmospheric fluidized bed combustion component test and integration unit (AFBC/CTIU) currently under design and construction by DOE was first conceived in mid-1975. The facility will develop and optimize hardware systems required for successful commercialization of utility

and industrial AFBC units. The size of the unit is such that prototype commercial scale components can be used, and yet the unit is small enough to allow rapid modification of equipment and substitution of components without requiring excessive renovations. Extensive instrumentation is incorporated so that all aspects of FBC and support system operation can be analyzed in detail.⁹

The major objectives of the CTIU include evaluation and testing of materials, components, and instrumentation and their integration into a workable fluidized bed boiler system. The specific objectives include:

- The testing of mechanical components, subsystems, and systems to develop optimum configurations.
- Investigation of the dynamic behavior and control of an integrated stacked multicell fluidized bed boiler.
- Evaluation and optimization of boiler internal configuration for emission control and stable operation.
- Provide rapid data dissemination through hands-on access for component designers, manufacturers, and research engineers.

The facility is tailored to allow easy access to components so that they may be modified or replaced with alternative hardware in the course of the test program. The actual development work will be stimulated in the private sector by providing access to a well instrumented test facility.

In order to meet the research goals for the project, the system includes the allowance for a greater overall flexibility than most facilities. The steam generator support systems are designed to provide for rapid configuration of operating modes, system controls, and actual hardware.

The steam generator is a vertically stacked three cell boiler as shown in Figure 9. The bottom two 6 ft x 6 ft cells are coal burning and the 3 ft x 3 ft carbon burnup cell is located at the top of the stack. The system is capable of obtaining velocities of 4 to 16 ft/sec with expanded bed height of two to eight feet. Gas retention times between the top of the bed and the convection tubes under these modes are in the range of .5 to 3 seconds.

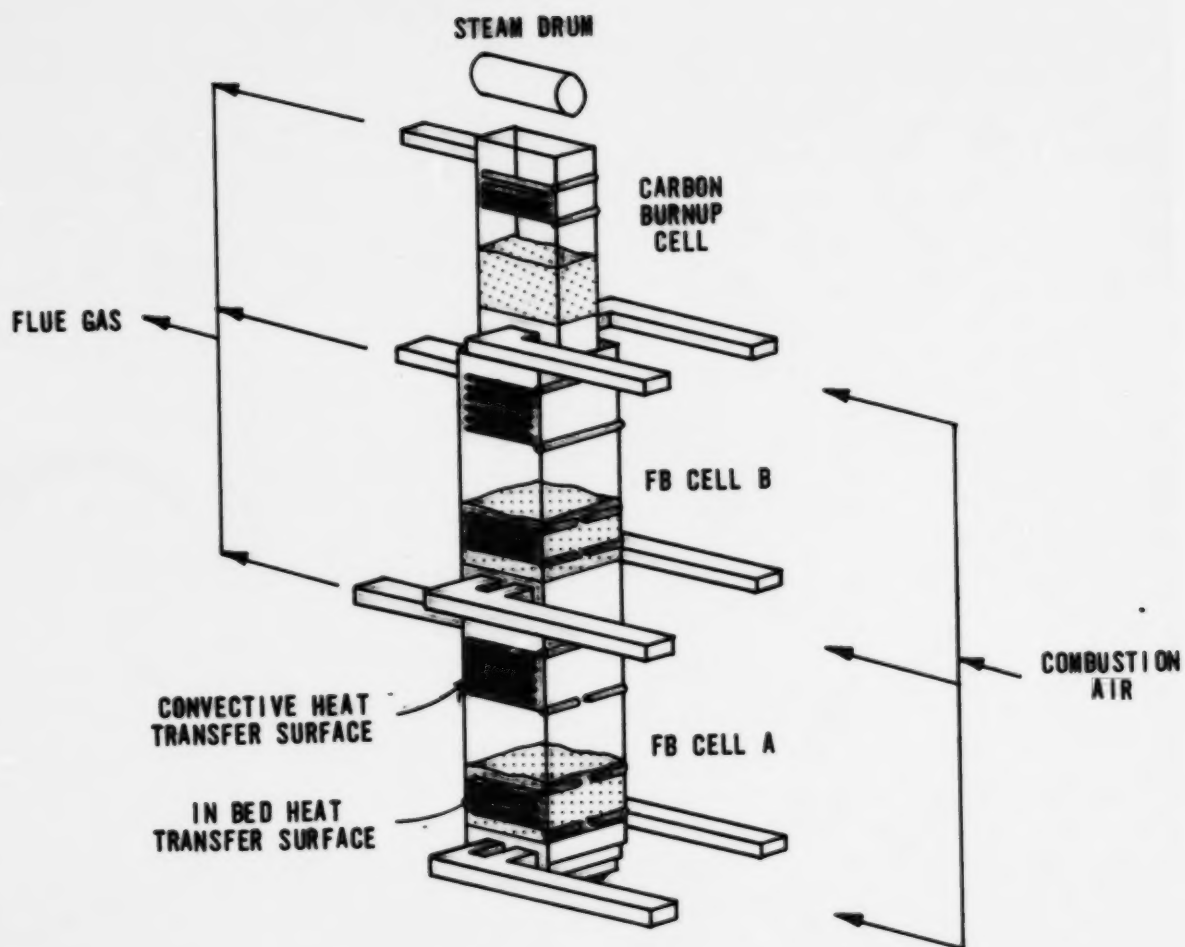
The basic configuration of the unit allows for removal and replacement of all tube bundles both inbed and above bed. Replacement bundles with different tube numbers, diameters, and spacing will be tested in the unit. By removing and replacing convective bundles, varying amounts of gas retention times are possible.

Another goal of the CTIU is to investigate the performance of the submerged tube bundles. Since the physical relocation of the bundles was quite difficult, another approach was developed. A movable distributor plate is employed which can be adjusted up to 24 inches.

Coal and limestone feed systems are designed for pneumatic conveying using dilute phase flow. The feed systems can be modified or replaced with other design alternatives for future tests. Material preparation and delivery are conventional in nature. Provisions are made for single or double screened feed, and all coal is capable of being dried to within one to two percent surface moisture. Coal up to one inch can be burned. The facility arrangement allows greater working space than commercial installations to provide room for installation of newer components as developed and to limit down time during installation.

The projects conceptual design was begun by DOE in the fall of 1975 and completed in the Spring of 1976. A/E selection was completed July 1976 followed by orientation and concept validation. Design of the basic structure was completed in August 1977. Bids received in November 1977

FIGURE 9
COMPONENT TEST AND INTEGRATION UNIT (CTIU)
TO DEMONSTRATE "STACKED BED" CONFIGURATION



were within the projected funds and were accepted by DOE. Construction began in spring of 1978.

The Morgantown Energy Technology Center CTIU project team has worked closely with EPA to incorporate sampling access points in the CTIU equipment and systems design for efficient and effective sampling. The facility will permit testing of the EPA mobile particulate control devices on a flue gas slip stream. The devices to be tested include a mobile scrubber, baghouse, and electrostatic precipitator. EPA will also provide inputs to the 30 months test plan being developed.

Within the FBC cells, there are several research areas that will be addressed. These areas include:

- Air distributor - type, location with respect to tube bundles, sealing methods and expansion tolerance.
- Tube bundle material - spacing, stresses, corrosion, and erosion factors.
- Solids, injection, and removal points - number, type, and location.
- Sectionalizing of air plenum - local fluidization for studying start-up and turndown.
- Freeboard height and above bed convective tube bundle location - for freeboard disengagement and quenching of combustion reactions.
- System control schemes - for operation of the unit to follow load demand typical of a utility installation.

Both a hard wired, analog control system and a parallel, direct digital control system will be installed with this facility. The two control systems will permit transfer from one system to the other during operation to test and compare the control algorithm.

The systems external to the steam generator which will be developed include:

- A fuel stream splitting system for controlling size and weight distribution to multiple feed points.
- A hot bed material (up to 2,000°F) handling system for removal, classification, storage, and reinjection of spent bed material into the combustion cells.
- A hot flyash stream transport system for storage, splitting, and reinjection of hot ash collected by the cyclones into either the carbon burnup cell or the main cells.
- Particulate removal systems for entrained ash.
- Calcium sulfate regeneration system as a design concept for future installation.

3.3.3 EPRI/B&W Development Facility¹⁷⁻²⁴

This project has been established as a cooperative Babcock and Wilcox (B&W)/Electric Power Research Institute (EPRI) effort to develop design data and accumulate operating experience from a 6 ft x 6 ft pilot scale fluidized bed development facility. This data will provide a basis for the design of demonstration and commercial atmospheric fluidized bed boilers (AFBC) for utility applications. Results from this project will be used in on-going commercial AFBC design studies sponsored by

EPRI (RP722), DOE, and TVA, in which the commercial viability of AFBC on a utility scale will be determined in 1980.

In 1975, B&W conducted a literature survey under an EPRI contract to ascertain the state of the art for AFBC applied to utility steam generators. The survey concluded that fluidized bed combustion presents a viable method of using noncompliance coal for utility steam generators. Several areas were identified that required further study before large-scale demonstration plants could be built. The fluidized bed development facility was designed to study these areas.

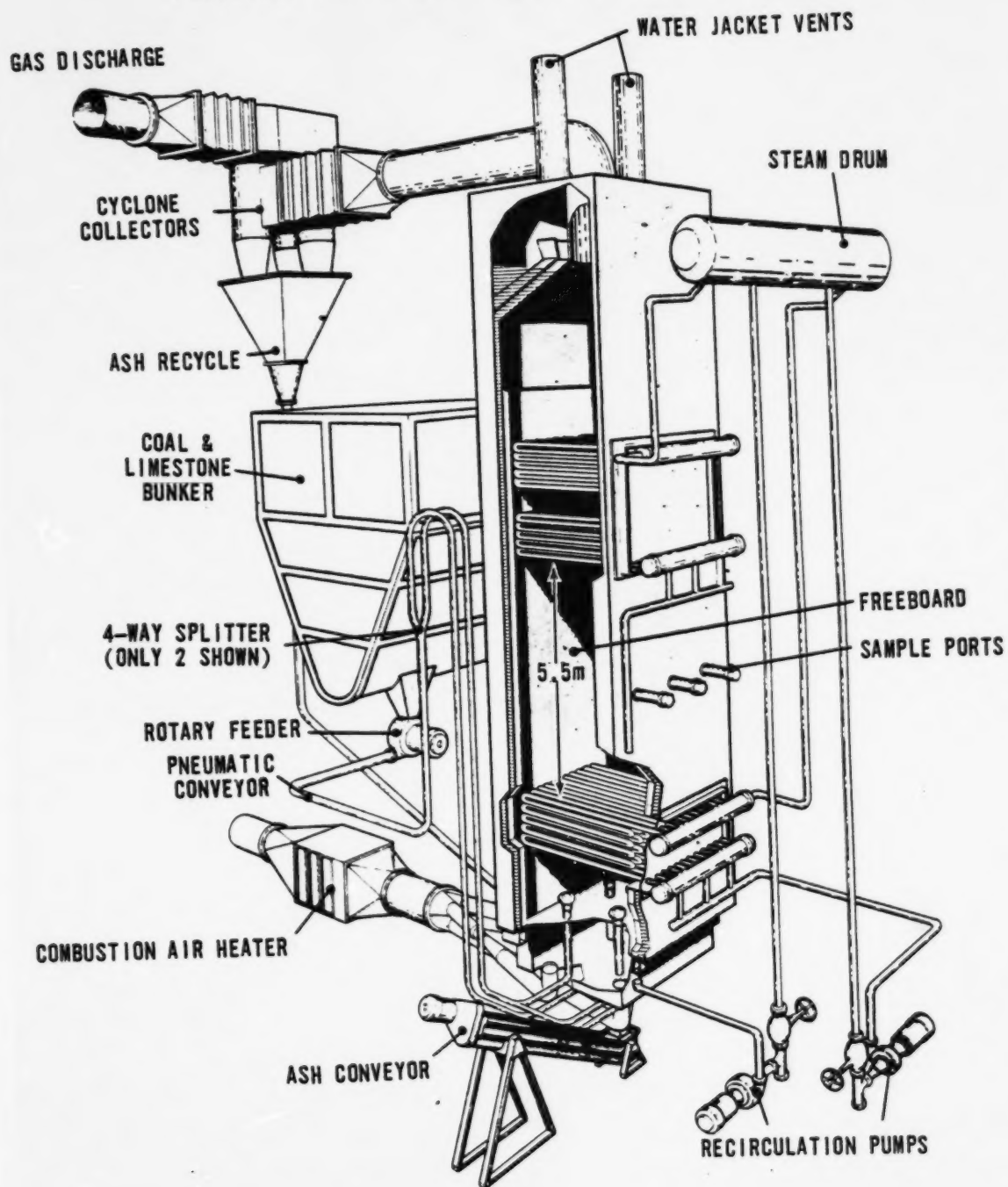
A key design parameter was that the test unit be large enough to require multiple coal feed points. Other design parameters are listed below:

TABLE 3
B & W FBC DEVELOPMENT FACILITY DESIGN PARAMETERS

Bed Area	6 ft x 6 ft
Superficial Velocity	8 ft/sec
Coal Feed Rate	1,880 lb/hr
Heat Rate	7 megawatt thermal (MWt)
Saturated Steam Production	10,000 lb/hr at 150 psig
Superheated Steam Production	2,000 lb/hr at 1,000°F
Bed Operating Temperature	1,600°F

The major components of the facility are illustrated in Figure 10. Coal and limestone are conveyed to the top of the boiler where they are crushed and transported directly to two separate bunkers. From the bunkers, coal and limestone are fed through separate weigh feeders into a common transport line. The feed solids are picked up by transport air and carried to a splitter where they are separated into four equal feed streams. These pass up through the windbox and distributor plate into the combustion zone of the fluidized bed boiler.

FIGURE 10
BABCOCK & WILCOX
FLUIDIZED BED COMBUSTION DEVELOPMENT FACILITY



A centrifugal blower supplies forced draft air to the fluidized bed. The blower is capable of delivering 6,000 cfm at a 60 in. water gauge head. This combustion air passes through a steam preheater and a direct-fired preheater before it diverges into the four separate air ducts supplying the windbox. Each of these ducts has a separate damper and venturi flowmeter for control and measurement.

The windbox has four compartments. This division allows certain sections of the bed to be "slumped" or isolated while the others function normally. Slumping will be studied as a possible means of turning down the boiler. Start-up and shutdown of the unit will also be facilitated by this windbox separation.

An 18 foot freeboard is located between the immersed tube bank and the convective tube bank at the top of the furnace. This height was chosen to permit heavy particles with a thermal settling velocity greater than the fluidizing velocity to fall back into the bed. This extended freeboard space should also help determine the reactions which take place in the freeboard and the degree of freeboard combustion. The 18 foot freeboard height was limited by the existing building.

Four cyclone separators are mounted at the furnace exit to collect particulates escaping from the furnace. Dampers on each cyclones can be adjusted to maintain reasonable velocities and improved collection efficiencies. Material collected by the cyclones can be recycled to the bed or removed by the ash handling system. Recycled material is fed from the cyclone hoppers through a watercooled conveyor. After passing over an in-line, impact flowmeter, the material flows through a downcomer to the transport air line in the coal and limestone feed system.

The facility has been operating since 1977, and results are being published in progress reports. Several problem areas have been identified and corrected. These areas include:

- Distributor plate design - The initial air distributor plate consisted of a woven nichrome wire mesh. This material was found to be unsuitable due to pluggage and was replaced with a perforated plate.⁵ The perforated plate operated for about a year but had persistent problems with warpage and leaks. It was recently replaced with a bubble-cap distributor plate.
- Wear of coal/limestone feed pipes - This persistent problem was not completely eliminated by several design changes. Carbon steel lines last only about 500 hr in this application.
- Vibration of tube bundle - This caused wear on the tubes and sway in the furnace. Bracing of the furnace and a firmer tube support structure has alleviated this problem.

The test facility has been operating with coal for over 2,000 hours since 1977. Major results include:

- Heat transfer coefficient - The measured overall heat transfer coefficient is very close to B&W's predictions of 45 to 50 Btu/hr-ft²-°F.
- Sulfur capture - Sulfur capture is better than predicted is attributed to the significant (i.e. 25 percent of total) sulfur capture occurring in the extended freeboard.
- Combustion efficiency - 10 to 15 percent of the total combustion occurs in the extended freeboard. The efficiency appears to vary with coal feed size, but tests to date do not cover a wide enough range to confirm the predictive model.

Near term testing with this facility will be directed towards further improvement in combustion efficiency. Planned test include:

- The effect of coal feed particle size.
- Feed point spacing greater than one feed point per nine square feet of bed plan area.
- The effect of recycling on particulate carryover.

Planned modifications to the unit include the addition of a bag filter system and allowance for an electrostatic precipitator at a later date.

3.3.4 Commercial and Demonstration Design Studies

In January 1977, contracts were awarded to Stone & Webster (S&W) and Burns & Roe (B&R) for conceptual designs of commercial utility AFBC plants. The B&R study was for a noncompliance Western coal, and the S&W study for a 2.5 percent sulfur Eastern coal. B&R selected Combustion Engineering (C-E) as a subcontractor, and S&W selected both Babcock & Wilcox (B&W) and Foster Wheeler (F-W). The conceptual designs were for a nominal 600 MWe power plant.

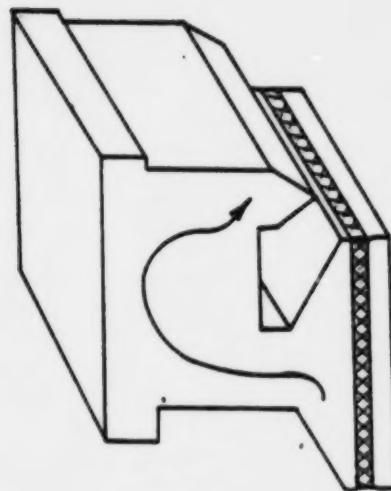
In parallel contracts, each of the three boiler manufacturers produced conceptual designs for a 200 MWe demonstration plant for the Tennessee Valley Authority (TVA). The demonstration plant design is a scaled down version of the commercial plant customized for TVA's particular needs.

The three conceptual designs for the commercial size plant are quite different in appearance, as shown in Figure 11. B&W produced a "split level" design that most clearly resembles a conventional boiler. C-E produced a "ranch style" that allows bottom support of the heavy beds. F-W designed a "high rise" that minimizes land requirements. Each design has merits and weaknesses and will be discussed in the following sections.

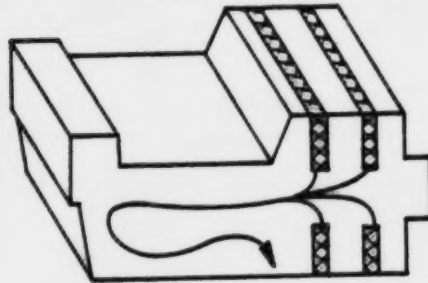
COMBUSTION
ENGINEERING

BARCOCK &
WILCOX

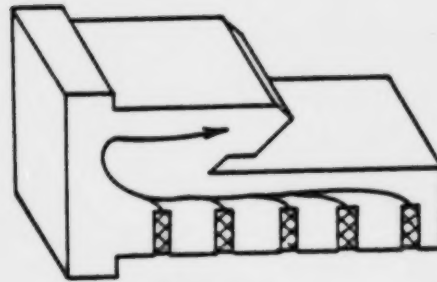
FOSTER
WHEELER



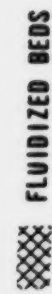
"RANCH STYLE"



"SPLIT LEVEL"



"HIGH RISE"



FLUIDIZED BEDS

FIGURE 11
COMPARISON OF THE CONCEPTUAL STEAM GENERATOR DESIGN
CONFIGURATIONS OF THE MAJOR BOILER MANUFACTURERS

3.3.4.1 Burns & Roe/Combustion Engineering^{10, 11, 12}

The overall objective of this program was to prepare a conceptual design for an electric power generating plant that will directly combust noncompliance Western coal in an AFBC and generate electric power in an environmentally acceptable manner. Noncompliance Western coal is defined as that typical of the Powder River Basin Region and/or the Green River Region in Wyoming. This coal cannot be combusted in a conventional coal fired boiler in an environmentally acceptable manner without the use of precombustion treatment or flue gas desulfurization.

The specific design coal is subbituminous coal from the Felix Bed in the Powder River Basin in Wyoming. It has a design sulfur content of 0.89 percent and a heating value of 8,053 Btu/lb and requires 46 percent SO₂ removal to meet the emission standard of 1.2 lb/10⁶ Btu. Allowance was made in the design for a sulfur content variation of from 0.89 to 3.25 percent.

Bed design characteristics were investigated early in CE's Fluidized Bed Combustion Studies. The selected values were adopted from the design used by Pope, Evans & Robbins (PER) in the Rivesville Multicell Fluidized Bed Boiler. (In fact, all three units use these values.) Three modifications were made for the 570 MWe unit conceptual design. The bed heat transfer coefficients have been increased approximately 15 percent over Rivesville design values. The coal/limestone feed rate was determined through extrapolation of BCURA data at lower bed velocities. For the 0.9 percent sulfur coal a calcium-to-sulfur ratio of 2.3 is estimated to provide the 46 percent sulfur removal required. For the 3.25 percent sulfur coal a calcium/sulfur ratio of 4.0 is estimated to be required to obtain 85 percent sulfur removal.

For the first generation fluidized bed steam generators, CE decided to use a 2,400 psig/1,000°F/1,000°F steam cycle with Controlled Circulation^R. Compared to a supercritical cycle, the subcritical cycle

has lower pressure part metal temperatures (thus, there is less potential for corrosion) and has fewer evaporator circuit differential expansion problems. In addition, boiler operation is simpler.

Several alternate unit layouts were investigated early in the TVA study. From this review, an arrangement with all the beds on a single operating level was selected. This arrangement has been named the "ranch style" and is shown in Figure 12.

The major reasons for selecting this unit arrangement were:

1. Operation is easier with all beds at control room level.
2. Maintenance is easier with beds near ground elevation.
3. There is easy access to coal/limestone feed and bed drain lines from below the unit.
4. Estimated capital cost is lower. Features resulting in lower cost include the use of fluidized bed modules which can be shop fabricated and rail shipped, a less complicated air duct and seal arrangement, a less complicated buckstay system, and bottom support of bed modules, which reduces support steel requirements.

The furnace at the bed elevation is 76 ft wide x 112 ft deep. Each bed module is 9 ft wide x 36 ft long with 2 ft. access spaces provided between modules and a 4 ft space at the unit centerline for access and main bed support steel. The furnace will be operated at a slightly negative pressure. The 5.5 in. predicted downward expansion of the hood is handled by a gas tight, high temperature, flexible fabric seal between the bottom of the hood and the top of the bed modules. This seal is protected from furnace heat and ash loading by a barrier of high temperature blanket insulation supported by a loose steel plate. A similar seal arrangement is provided between bed modules.

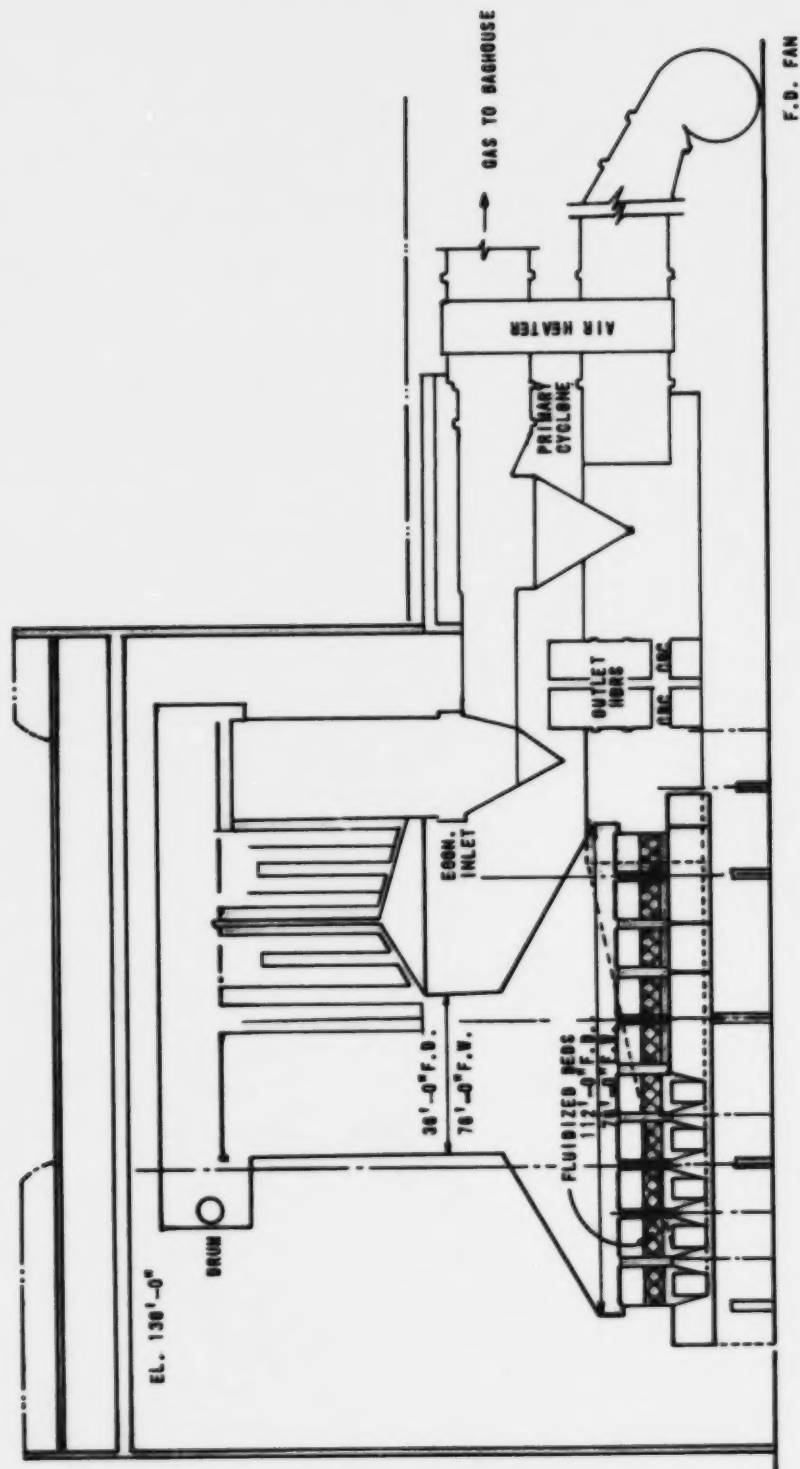


FIGURE 12
COMBUSTION ENGINEERING "RANCH STYLE" 570 MW
FLUIDIZED BED STEAM GENERATOR CONCEPTUAL DESIGN

The superficial velocity is 12 ft/sec for the main beds and 9 ft/sec for the carbon burn up cells. The excess air for the main beds is 20 percent and 25 percent for the carbon burnup cells 25 percent. Bed operating temperature is 1,550°F for the main beds and 2000°F for the carbon burnup cells. Static bed depth is 24 inches, and full load bed depth is 48 in. Grid plate pressure drop is 16 in. and freeboard height is six ft. The combustion efficiency for both main bed and carbon burnup cells is estimated to be 90 percent.

Combustion air from the forced draft fans is heated by the air heaters to 665°F and ducted to the main bed plenums. The air flows up through stainless steel perforated grid plates into the beds, where coal and limestone fed by transport air are fluidized and the coal combusted. The products of combustion are cooled by steam generating, superheating, and reheating surfaces, and pass through primary cyclone separators to remove elutriated material consisting of unburned carbon, limestone, and coal ash. This material is returned to the fluidized bed carbon burnup cells which are provided with combustion air from the same source as the main beds. The CBC off-gas is cooled to 800°F by evaporator and economizer surfaces and then passes through secondary cyclone separators, with the elutriated material is removed. The flue gases leaving the primary and secondary cyclones mix before the air heaters which cool the gas to 242°F. The exhaust gases then pass through bag filters to remove the remaining particulate matter to meet pollution control requirements. Material drained from the fluidized beds is cooled before disposal by air which is then discharged upstream of the air heaters to recover heat.

The coal/limestone feed system will transport 1/4 in. x 0 sized coal and 1/8 in. x 0 sized limestone from the bunkers to the main and CBC beds. Coal and limestone are metered by gravimetric feeders and mixed in surge hoppers at the entrance to the feed pumps. The material then enters a chamber where 25 psig air is introduced through a series of air jets and is conveyed into the dense phase transport line. The

material goes through two comb type splitters in series: first a 4:1 split, then a 9:1 split, to obtain a distribution in the bed of 18 ft² of bed area per nozzle.

The coal/limestone air mixture penetrates the grid plates from below and enters the fluid beds. Silicon carbide nozzles divert the flow horizontally.

Tests are being run to determine turndown, using 1/4 in. topsize coal mixed with 1/8 in. topsize limestone in a 3-to-1 ratio. The tests will also determine the moisture level limit of this system and attrition rates.

The primary cyclone separators collect unburned carbon elutriated from the main beds for recycle to the CBC beds. It is estimated that 37 percent of the collected particulate matter is carbon. A conservative design efficiency of 90 percent will result in a carbon loss of 1.9 percent.

A baghouse was selected for final stage particulate clean-up. The uncertainty in particulate resistivity and particle size distribution makes it difficult to economically size an electrostatic precipitator to meet EPA emission standards. The baghouse is insensitive to particle matter resistivity, composition, and flow rate. It will also cost less than a precipitator.

3.3.4.2 Stone & Webster/Babcock & Wilcox^{13, 14, 15}

In January 1977, a contract for the conceptual design of a commercial size electric power steam generating plant using an AFB boiler was awarded by DOE/ERDA to Stone & Webster Engineering Corporation in conjunction with Pope, Evans & Robbins. The project approach was to use a pulverized coal/wet scrubber power generating facility currently being designed as a reference. AFB boilers were substituted by boiler

manufacturers for the pulverized coal fired boilers and scrubbers, and the technical and economical feasibility of this design approach was determined. Two major boiler manufacturers were awarded contracts to design 570 MWe AFB boilers. The boiler manufacturers selected were Babcock & Wilcox (B&W) and Foster Wheeler (FW).

The basis for the B&W design is as follows:

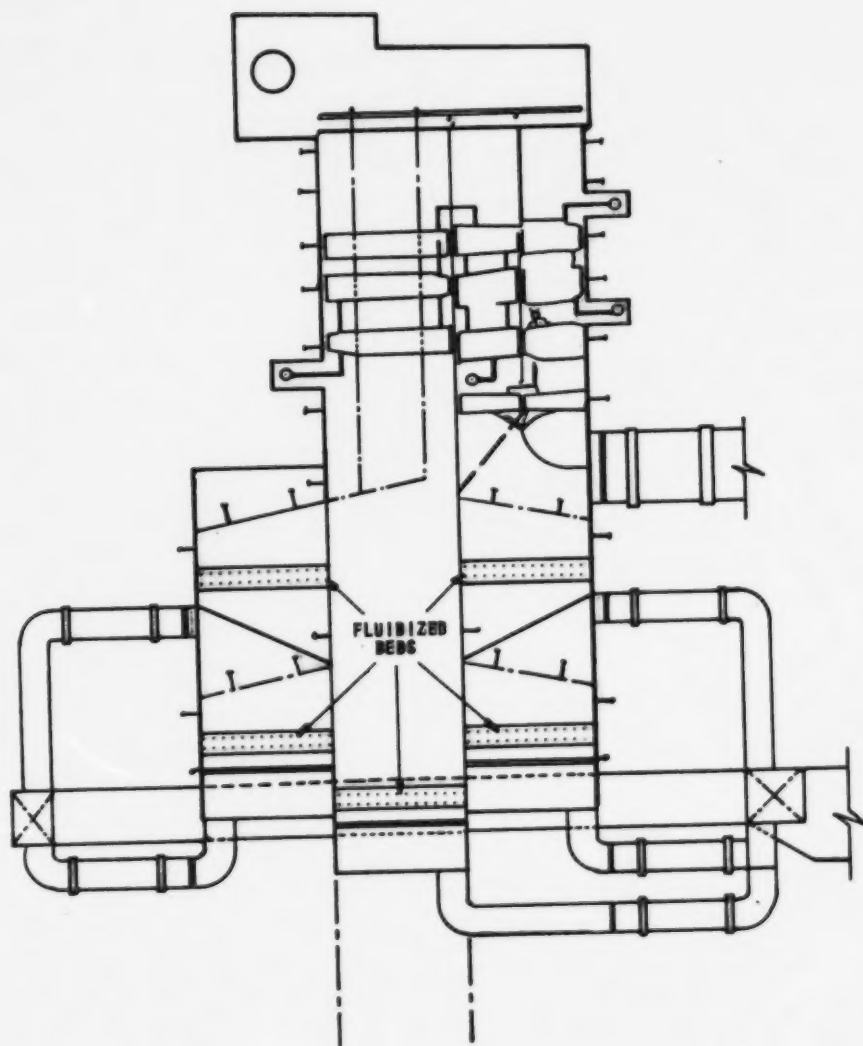
- Bed depths of four feet with a superficial velocity of eight ft/sec.
- Main bed temperature of 1,550°F and a CBC bed temperature of 2,000°F.
- Combustion efficiency of 88 percent for both FBC and CBC. Of the 88 percent combustion, 91 percent was treated as occurring in the beds, with the remaining nine percent in the freeboard area immediately above the beds.
- The calcium-to-sulfur ratio is estimated to be 2.5.

The following summarizes the boiler related design criteria used and the reasons for their choice:

- A pump assisted drum type boiler was chosen vs a once-through design. This design permits the use of larger diameter tubes for structural reasons. It also eliminates the multiplicity of furnace passes that would be required to obtain sufficient mass flows to assure adequate wall tube cooling and facilitates start-up the unit by eliminating the need for superheater by-pass to establish boiler water flow prior to firing.

- A single, large unit shown in Figure 13 was chosen for the conceptual design rather than using multiple small units.
 - Multiple small units add to the operational complexity.
 - Controls must be provided to coordinate the feed water flow and fuel flow to each of the units as well as for overall load control.
- Steam side design is based on series rather than parallel flow.
- The design follows conventional utility boiler practice and is top supported.
- No reheater surface is located in the beds. This eliminates the need for a by-pass system to protect the reheater during start-ups shutdowns, and unit trips.
- A design with partially stacked beds and a separate CBC.
- All of the surface in the carbon burn-up cell is boiler surface in parallel with the circulating system.
- Coal and limestone are pneumatically fed to the beds by injectors which penetrate the air distributor plate from below.
- Superheat temperature and steam flow are controlled by placing bed compartments into service or removing them from service (slumping).
- A hot precipitator collects unburned carbon rather than using mechanical dust collectors. A savings of approximately one percent in boiler efficiency is realized due to the higher carbon collection efficiency of the hot precipitator.

FIGURE 13
BABCOCK & WILCOX "SPLIT LEVEL"
570 MW, FLUIDIZED BED STEAM GENERATOR CONCEPTUAL DESIGN



In the B&W design, preheated air, coal, and limestone are fed to the FBC where most of the heat is released. As the flue gas passes through the boiler, it is cooled to 725°F. The gas flows through a hot electrostatic precipitator where the particulates are removed. The solids collected in the precipitator are directed to the CBC where preheated air is used to burn this char.

The flue gas from the CBC is cooled to 750°F, passes through a mechanical dust collector and a separate electrostatic precipitator, and is combined with the FBC flue gas. The gas then flows through the air preheater, the ID fans, and is discharged to the stack at 270°F.

The main FBC is equipped with five fluidized beds, each 71 ft x 24 ft. Each of the main beds is divided into five compartments, all with separate fuel and air controls. This arrangement provides operational flexibility by means of bed slumping. Horizontal heating surface is located in each fluidized bed. One and one-half beds contain boiling surface, and three and one-half contain super heat surface.

The carbon burn-up cell is made up of four fluidized beds each 10 1/2 ft x 52 ft and separated by water cooled walls. No in-bed heating surface is contained in the CBC. A bed temperature of 2,000°F is obtained by removing the heat with the membrane boiler walls.

Coal and limestone feeders operate together to provide the proper coal-to-limestone ratio. Both feeders discharge to a common chamber. The coal/limestone passes through a rotary/pressure seal into a mixing bustle where hot primary air and transports the materials. The flow splits into 40 streams for feeding the main bed compartments. The individual injector feedlines pass through the air distributor plate and into the bed on approximately three foot centers.

3.3.4.3 Stone & Webster/Foster Wheeler^{13, 15, 16}

The operating parameters selected for the Foster Wheeler design are:

TABLE 4
OPERATING PARAMETERS FOR 570 MWe AFB UNIT

	<u>FBC</u>	<u>CBC</u>
Bed depth, ft	4	4
Bed operating temperature, °F	1,550	1,900
Fluidizing velocity, ft/sec	10	8
Excess air, %	20	30
Freeboard height, ft	12	12
Calcium-to-sulfur ratio	2.1	-
Fuel size	1" x 0	-
Sorbent size	3/16" x 0	-

Foster Wheeler has selected the once-through steam cycle. This design uses circuitry consisting of heated risers coupled to unheated downcomers. The circuitry results in a pressure part weight of approximately 60 to 80 percent of a similar size, subcritical, drum type, forced circulation, AFB unit. This weight reduction is due primarily to the elimination of the steam drum and forced circulation system manifolds, downcomers, feeders, and risers.

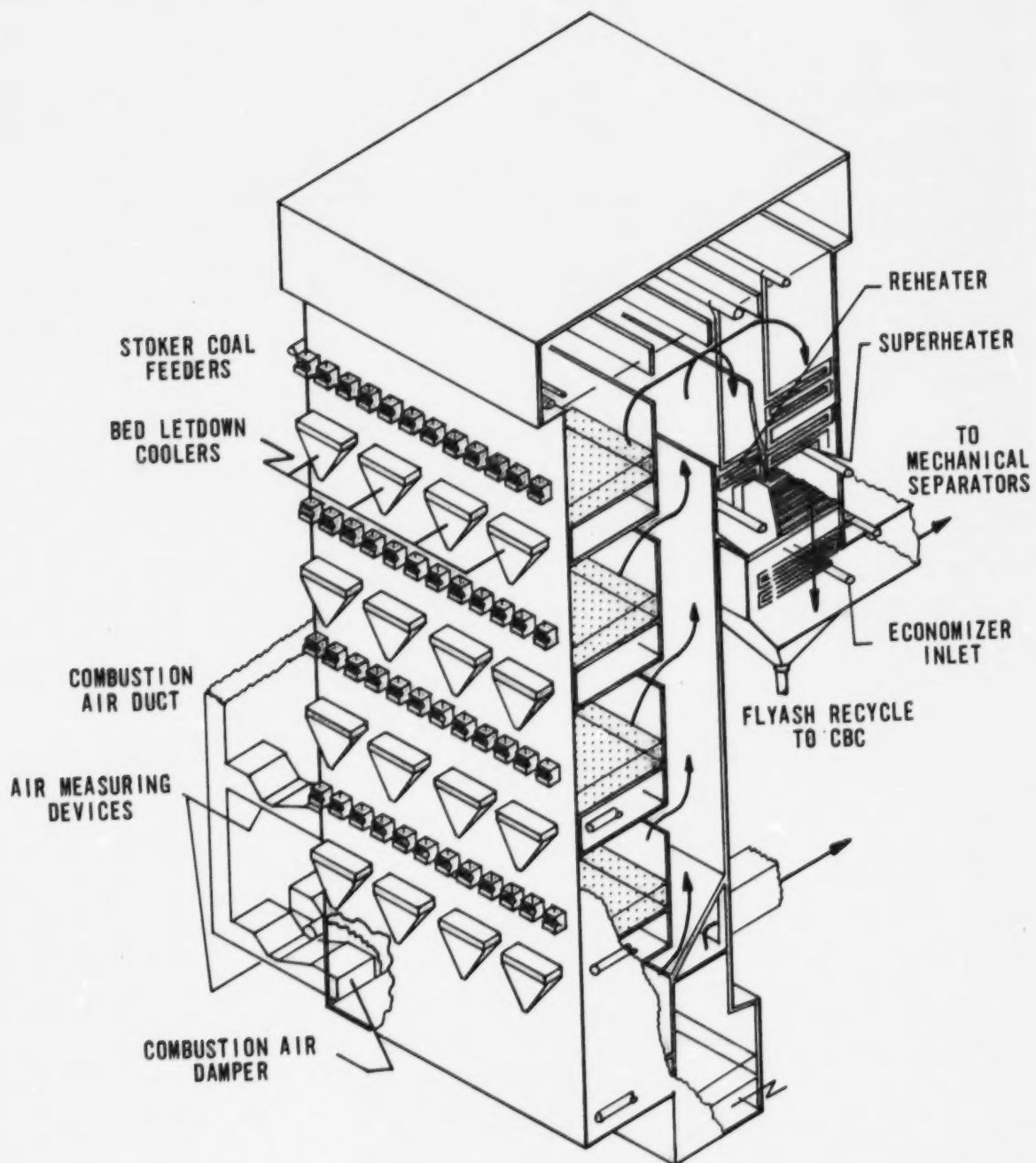
Foster Wheeler has included the steam to heat by-pass system coupled with the once through design to enhance operating capability during start-up, cycling, and emergency shut-down. This system, which by-passes the steam around the high pressure turbine to the reheater and condenser, has the following advantages.

- Throttle steam conditions to the turbine can be regulated by firing additional super heater or reheater segments as required.
- Safety valve lifting is avoided since steam may be directed to the condenser when the turbine intercept and control valves are closed.
- During a turbine trip steam flow is maintained to the superheat and reheat circuitry by way of the by-pass system.
- Turbine erosion during start-up is minimized due to the ability to flush the high pressure and reheat circuits to the condensor.

In the Foster Wheeler design shown in Figure 14, the carbon burnup cell is an integral part of the boiler. The FBCs are approximately 22 ft x 60 ft with the CBC 20 ft x 60 ft. Each FBC and CBC is further divided into individually controlled segments to provide increased unit control and turndown. The FBCs are arranged in a vertical stack with heat transfer surface provided in each bed zone and arranged for boiling, reheat, and superheat duty. The vertical stack arrangement has been selected for the AFB design for the following reasons:

- Minimum plan area requirements.
- Balanced heat flow to steam generator circuits.
- Conventional wall circuitry and mechanical design.
- Coal feed from front wall with flue gas exiting from unit rear.
- Conventional parallel pass heat recovery area.

FIGURE 14
FOSTER WHEELER "HIGH RISE" 570 MW
FLUIDIZED BED STEAM GENERATOR CONCEPTUAL DESIGN



For the main bed cells, fuel is fed through the use of overbed spreader feeders located in the front wall. Limestone is gravity fed just above the expanded bed surface at the rear of the cell sidewalls. Spent bed material is extracted from the bed through the use of letdown coolers located along the front wall beneath the fuel feeders.

Coal burn-up in the FBCs has been set at 89 percent. Of the solids elutriated from the main beds, approximately 92 percent will be collected in the heat recovery area hoppers and main cell mechanical separators. This collected fly ash will be pneumatically transported and injected into the CBC through an array of nozzles. 90 percent of the remaining carbon will be combusted in the CBC.

The flue gas passes through the air heater and enters a baghouse collector for final clean-up. Baghouse collection was selected because of its extremely high collection efficiency and insensitivity to particulate chemical composition. Investigations into the suitability of hot and cold precipitation for the AFB indicated that insufficient data is available to support the use of precipitation for AFB with the low levels of sulfur and sodium in the fly ash.

The coal feed uses the overbed spreader feeder system to distribute coal uniformly to each of the bed segments. The advantages of this system are:

- Reduction in fuel feed points from one per 9 square feet of bed area to one per 110 square feet of bed area.
- Reduced potential for fuel line pluggage and erosion problems.
- Simplified fuel distribution system with the reduction in the number of feed points.

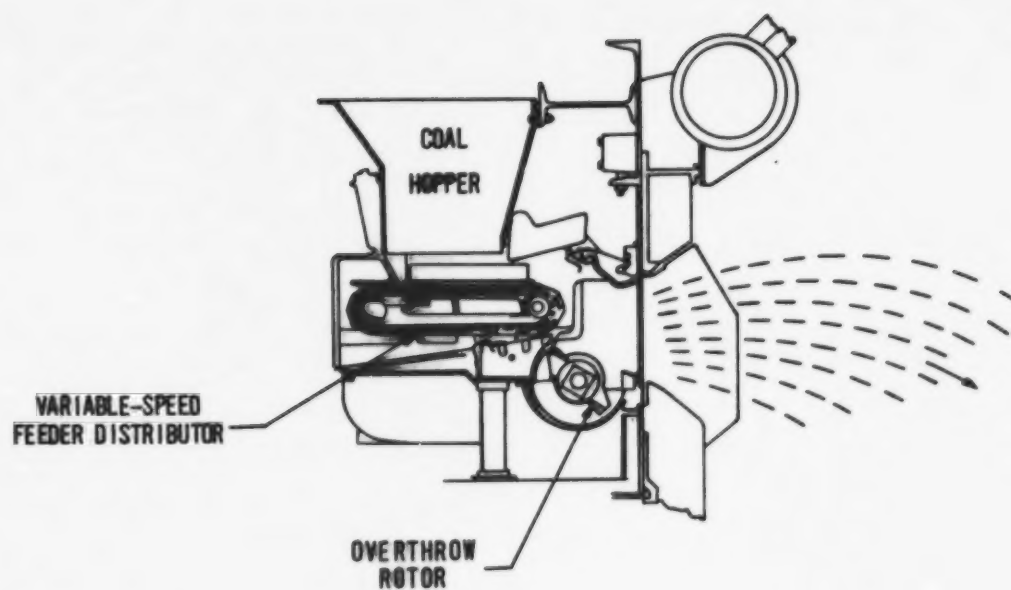
- Elimination of fuel dryers.
- Elimination of pneumatic transport system which includes pumps, piping, and controls.
- Simplified feed system monitoring because of reduced feed points.
- Reduced potential for maldistribution which can occur with plugged underfeed nozzles and distributors.
- Reduction in crushing requirements since the overbed feed system should handle conventional stoker coal (1-1/4 in. x 0).

A typical spreader feeder is shown in Figure 15. It consists of a small hopper which directs coal onto a distributor. The distributor moves the coal horizontally onto a rotor. This rotor rotates and propels the coal into the furnace. The rotor speed can be varied to suit the coal moisture and size distribution and to control the feed distribution. Coal feed rate is varied by adjusting the speed of the feeder. Each spreader supplies fuel to an area approximately 5-1/2 ft wide x 22 ft deep.

The stacked bed arrangement makes use of continuous monolithic welded membrane walls to form the enclosure and partition walls. The unit is top supported by suspension steel in the conventional manner. Buckstay support of the unit nearly duplicates a pulverized coal unit and as a result, standard stiffening systems are used.

In general, compared to other designs, the Foster Wheeler design has less area, volume, and support requirements because of its once-through, stacked bed design with integral CBC.

FIGURE 15
VARIABLE SPEED CHAIN DRIVE TYPE FEEDER



S&W examined the unit performance for both B&W and F-W AFB designs at 100, 75, and 50 percent load. For both designs, unit output increases because the steam required to reheat the stack gases required by the FGD in the base case can expand through the turbine. In addition, the unit heat rates for both designs show an improvement over the base case at all loads considered. The additional plant cost is justified in both cases.

Total owner life cycle costs favor the AFB case slightly. Refinement of AFB designs are expected to decrease the capital costs from those reported in this study. This, coupled with the expected improvement in cycle performance, would favor the AFB.

3.4 KEY TECHNICAL ISSUES

3.4.1 Sorbent Regeneration, Disposal, and Commercial Use

The possibility of regenerating the spent sorbent from the FBC is under active investigation for the potentially significant advantages it may offer, namely, sulfur recovery, reduced sorbent supply, and reduced spent sorbent disposal. However, because of the technical problems and current projected economies, regeneration is not presently being planned for inclusion in pilot and demonstration plant development work being funded by DOE. ANL is continuing to investigate the regeneration process and mechanisms at the benchscale level³⁹. Regeneration development work at the Exxon Mini-plant is also continuing.⁴⁰

An alternative to limiting calcium-based spent sorbent production by sorbent regeneration is to utilize some other granular sorbent material in the place of calcium-based sorbents. The alternative sorbent would be successful if it were highly regenerable and free from loss in physical integrity, while resulting in acceptable plant performance and economics. The possibility that there exists alternative sorbents for

SO₂ absorption that are superior to naturally occurring calcium-based sorbents (limestones and dolomites) in terms of performance and economics has been the subject of several screening studies.

Solid residue from the FBC process consists of spent sorbent and ash from the bed as well as a mixture of sorbent and fly ash removed from the flue gas by the particulate control equipment. Factors affecting the final composition include composition of the fuel, composition of the limestone or dolomite additive, and FBC operating conditions. The solid waste produced by an FBC system differs considerably both physically and chemically, from that produced by a conventional combustor with an FGD system. Some of the differences are:

- Residues from FBC are combined lime, CaSO₄, fly ash, and bottom ash, and they differ from the dolomite or lime scrubber sludges and conventional fly and bottom ashes. The flue gas scrubber desulfurization sludges may also contain fly and bottom ashes.
- FBC normally produces solid residues, whereas conventional combustion scrubbers produce liquid sludges.
- FBC residue samples have higher specific gravities than conventional fly ash.
- FBC operates at lower combustion temperatures (1550-1750 °F) and thus generates significantly less slag in the residues.

BCURA⁴¹; Pope, Evans and Robbins⁴²; and Westinghouse⁴³ have investigated the properties of the leachate obtained from the coal ash and limestone waste. Ralph Stone and Co. has just completed an environmental assessment of solid residues generated by fluidized bed coal combustion. Tasks included chemical and physical residue characterization, laboratory leaching studies, and testing of residues in various materials and agriculture applications⁴⁴.

Commercial uses for the spent FBC stone material are being actively investigated, mostly under funding by DOE. The major obstacles to using the spent stone are the very large volumes generated saturating the market transportation costs and availability of competitive raw materials. Fly ash and bottom ash from conventional boilers have been used in a number of products for years but at present only about 20 percent of the total production is utilized⁴⁵. This indicates that the market in this area for spent stone may be limited.

Other new uses that have been considered for spent FBC stone include fired products - bricks, hot press sintering pipes, and metal coatings; gypsum products - wallboard and plaster; and mineral recovery. Treatment of acid mine drainage is also a potential use for spent FBC stone.

A program is currently underway at TVA to collect additional data on the potential beneficial use of FBC solid waste on peanut crops in Alabama. The TVA program will determine the maximum nontoxic loading rates of FBC waste for various soils and crops. Other agricultural utilization studies for FBC wastes are being conducted by the U.S. Department of Agriculture under contract to DOE⁴⁶.

Descriptions of current projects follow:

- Studies of PFB Coal Combustion Process - Sorbent Regeneration⁴⁰ (Exxon Research and Engineering). A process was developed for continuously regenerating sulfated limestone or dolomite sorbent in a fluidized bed by reaction with a reducing gas at about 2000°F and high pressure. Experiments were completed in which batches of sulfated sorbent were regenerated in the mini-plant regeneration vessel. In those preliminary tests, up to 3.7 mole percent on a dry basis of SO₂ was produced and reduction of CaSO₄ to CaO was nearly complete. The agglomeration of the fluidized bed was avoided by careful control of temperature. The regenerator was

coupled to the miniplant combustor so that sorbent could be continuously recirculated between the two vessels and a 125 hour run was completed. The operability of this system was demonstrated in a five day run in which both the combustor and regenerator operated without interruption.

Additional combined combustor regenerator runs are now underway to study the effects of performance of the important variables, including sorbent recirculation rate, regenerator temperature, and type of sorbent. It is hoped to determine which combustor and regenerator operating conditions provide, simultaneously, low emissions of SO and other pollutants from the combustor, high concentrations of SO₂ in the off-gas from the regenerator, low makeup rates of fresh sorbent, and moderate recirculation rates between combustor and regenerator.

- Environmental Assessment of Solid Residues from Fluidized Bed Fuel Processing⁴⁴. (Ralph Stone and Co., Inc.) The overall purpose of the proposed work was to determine the environmental impact of the disposal of residues from the fluidized bed combustion of high sulfur coal and fluidized bed gasification of high sulfur residual oil.

A comprehensive program of residue characterization was initiated to determine the chemical and physical properties of the six fluidized bed residues. The resultant physical property data was used to hydraulically design 36 pilot test columns for leachate studies. The resultant chemical property data was used to determine the constituents to be monitored during the test columns study.

Studies were undertaken to determine the possibility of recovering and marketing the residues instead of disposing of them. The results of bench tests were used to evaluate the residues' uses in

the manufacturing of certain commercial products. These tests compared the properties of the recovered product with that produced using conventional raw materials. The use of residues in concrete, asphalt, soil cement, lime-fly ash aggregate and lime-fly ash-cement aggregate mixtures, and as load bearing fill were evaluated. Concurrent with the product feasibility task, an evaluation of requirements for treating residues was made to see if pretreatment can enhance product use or is required for disposal.

Potential use of the spent residues as soil conditioners for agricultural purposes was also investigated. A variety of crops (tomato, spinach, and lettuce) were grown in mixtures of fluidized bed residue and soil. The use of the residues as a soil conditioner and neutralizer of acidic soil was evaluated. Acidic soils may contain high levels of boron and manganese which are easily soluble and sometimes believed to be toxic to crops; however, it has been known for a long time that an increase in pH will decrease the uptake of heavy metals. Lime has been used to help increase the pH, but the residues could presumably replace the lime and thus decrease these toxic metals. Conversely, residues provide an excellent source of trace metals and nutrients needed by plants.

- Initial Assessment of Alternative SO_2 Sorbents for FBC⁴⁷. (Westinghouse Research Laboratories) Alternative metal oxide SO_2 sorbents for regenerative FBC power plants were screened on the basis of thermodynamic projections of desulfurization and regeneration performance. Estimates of sorbent availability and regeneration process economics were utilized to project maximum tolerable rates or sorbent loss by deactivation, attrition, preparation wastage, etc. Critical performance requirements and development needs are defined. Alternative sorbents having the greatest potential were identified.

- Development of Potential Uses for the Residue from FBC Processes⁴⁸. (L. John Minnick). In view of the potential for the FBC system, it is desirable to evaluate the by-product residue to determine its potential as a source of chemical components that may have commercial use. The current program is designed to expand on the original investigations (exclusive of agricultural uses). Major emphasis is on following:
 - Identification of the various components existing in the by-product material.
 - Evaluation of different alternatives for separation or beneficiation of these materials.
 - Performance testing to determine feasibility for use in commercial application.
 - Conduct of several small demonstration projects to verify the performance of the materials in specific applications.
- A Comprehensive Agricultural Research Program for FBC Wastes⁴⁶. (USDA, Agricultural Research Center). This agreement between the United States Department of Agriculture, Agricultural Research Service (ARS) and the Department of Energy provides for an intensive research program to evaluate the spent bed material from FBC for potential use in agriculture. The work involves a detailed chemical and physical analysis of the material and extensive greenhouse, growth chamber, and field studies.

3.4.2 Sulfur Capture

The use of fluidized bed combustion technology in boilers is rapidly becoming commercially feasible - small size boilers (up to 25,000 lb/hr of steam) are now being offered. Two larger scale demonstration units

(50,000 and 1000,000 lb/hr of steam), funded through the U.S. Department of Energy (DOE), are now under construction. A recent DOE Program Opportunity Notice anticipates a cost sharing program for the design/construction/operation of several more industrial fluidized bed boilers. How rapidly the technology is commercialized will depend primarily on two factors: the performance of the demonstration units and the impact of industrial boiler emission standards which are now being formulated.

The U.S. Environmental Protection Agency (EPA) is scheduled to promulgate New Source Performance Standards (NSPS) for industrial boilers by September 1981 and is now compiling background information necessary to formulate these standards. The NSPS for utility boilers is probably the best guide (although an upper limit) to what the standard may be. Generally, pilot and bench scale fluidized bed combustion data indicate that the former utility NSPS ($1.2 \text{ lb SO}_2/10^6 \text{ Btu}$ or approximately 80 percent sulfur reduction) can be met at a reasonable Ca/S ratio (~ 3). Meeting the present NSPS (85 percent sulfur reduction for emerging technologies including fluidized bed combustion) has been demonstrated in a few pilot and bench scale runs at a Ca/S ratio of three to four.

The major design factors effecting sulfur capture include the Ca/S ratio, the gas residence time, and bed particle size. In present industrial designs, the Ca/S ratio ranges from three to four, the gas residence time from 0.43 to 0.56 sec, and the limestone feed top size from 3/16 in. to 1/8 in. Sulfur capture, based on pilot and bench scale studies, is projected to be on the order of 85 to 90 percent. In present designs, sulfur capture will be increased, if necessary, by increasing the Ca/S ratio.

While the data from small scale units are promising, these experimental units are orders of magnitude smaller than proposed commercial units. Extrapolation of pilot and bench-scale studies may not be reliable for

estimating SO_2 emissions for larger demonstration and commercial scale units because scale-up of gas-solid interactions is especially difficult. Test programs will collect emission data as the commercial size demonstration plants come on stream.

In the event that SO_2 control is poor, a number of design and operating changes have been proposed to increase sulfur capture.⁽⁵³⁾ These include:

- Increasing Ca/S ratio
- Increasing gas residence time by
 - Decreasing fluidizing velocity
 - Increasing bed height
- Decreasing average bed particle size

Increasing the Ca/S ratio will increase sorbent needs and lower plant efficiency and thus significantly increase plant costs. The primary effect of reducing fluidizing velocity is an increase in boiler size. Increasing bed depth significantly increases bed pressure drop and fan power requirements. However, the effect on overall plant performance is relatively small. Reducing bed particle size will result in an increased entrainment rate resulting in much higher dust loadings. These higher dust loadings could seriously increase the corrosion and wear in the boiler convection surfaces. In general, design changes required to increase sulfur capture tend to make operations and maintenance more difficult and to reduce the inherent advantage of fluidized bed boilers over conventional boilers.

Present fluidized bed boilers are significantly more expensive than stoker fired boilers and probably more expensive than suspension fire units. Fluidized bed boilers appear to have a potential cost advantage over conventional boilers with SO_2 scrubbers but the magnitude of this advantage is uncertain. Design changes to increase sulfur capture

reduce the performance and cost advantages of fluidized bed combustion, and this could result in a set back for the adoption of this technology.⁵⁴

3.4.3 Coal Feeding⁶⁵

Simplicity and reliability are of the utmost importance in designing a feed system for an AFBC utility application. The solids feeding system for a fluidized bed combustion system must produce material flow into the combustion unit in a reliably uniform and continuous fashion. In addition, for the large scale utility size steam generating units, the design of the system should be as simple as possible to avoid accessibility and maintainability problems caused by equipment component congestion.

Combustion Engineering and Babcock & Wilcox are both relying on the underbed feed approach with air as the transport medium. Coal and limestone fed at the base of the bed have the maximum time for reaction. Data have also shown that gas-solid mixing is more favorable near the air distributor where the bubbles are small and the contact area between the air and the particulate phase (coal and limestone) is large.

This could therefore be the optimum point of material feed from the standpoint of combustion efficiency and sulfur capture. Underbed feed also has historical operating precedence on smaller units. Babcock & Wilcox chose the historical feedpoint spacing of $9 \text{ ft}^2/\text{feedpoint}$. C-E specified $18 \text{ ft}^2/\text{feedpoint}$. The fluidized bed itself should operate reliably at either of these values, though the maximum bed area per underbed feedpoint has not yet been determined. This determination will be estimated first by combustion efficiency studies and then more accurately determined after long term (several years) operation of an AFBC which will allow boiler performance and material selections to be verified.

The biggest problem with these small areas per feedpoint is in equally and continuously dividing the solid stream flows prior to injection. C-E is requiring the combined coal and limestone streams to be split into 36 streams from one, and the B&W design has multiple 40:1 solids splitters. This is not a proven technology for the AFBC applications, and such solids handling would have to be demonstrated before the designs could be built. In addition, the accessibility, reliability, and maintainability of such splitter systems could be questioned, particularly in regard to the possibility of feeder tube pluggage.

Foster Wheeler (FW) has presented a design that greatly reduces the required solids stream splitting, but at the same time introduces the uncertainties of an untried overbed feed. The FW design uses spreader stokers placed on five foot centers across the length of the bed which are fed from coal bunkers via gravity filled chutes. This system requires that the coal bunkers be approximately 300 feet above grade and that they be filled by an extraordinary tripper conveyor system. The conveyors are an unusual but not impossible extension of existing technology, and the chutes leaving the coal bunkers have only a 3:1 split on each of five levels. By using spreaders the FW design has one feedpoint per 110 ft^2 of bed area.

Foster Wheeler has made an imaginative approach to solving the solid stream splitting problem, but, along with the previously mentioned hardware problems, feeding coal into the freeboard raises further questions. The distribution pattern of the coal that falls into the bed and its effects are unknown. If this distribution is unbalanced the bed might not operate properly and the possibility of creating varying oxidizing and reducing zones would be great. The coal fines fed overbed may never reach the bed, but might instead be elutriated raising the possibility of freeboard burning. If freeboard burning were to occur, sulfur capture would be decreased, heat recovery zone requirements would be altered, and furnace temperatures could be so

high as to make NO_x and slagging serious problems. Foster Wheeler is suggesting this will not be a problem because the surface moisture of the coal will cause many of the fines to adhere to the larger sized coal feed and, thus, be combusted in the bed.

3.4.4 Combustion Efficiency^{56,57}

At the required bed temperatures, fluid bed combustion efficiencies are poor compared to conventional utility boilers. This requires carbon burn-up beds or reinjection to partially compensate for this inefficiency.

High combustion efficiency of coal in an atmospheric fluidized bed has not yet been conclusively demonstrated. Approaches such as bed recycle and carbon burnup cells have been used, but both have disadvantages. Recent evaluation has led to the hypothesis that poor combustion efficiency is due to the wide-range of particle sizes in the coal feed. That is, since the coal feed is not monodispersed, it is believed that a mid-range of particle size exists that does not burn due to insufficient residence time but is carried out as unburned carbon.

Usually, 10 to 15 percent of the heat input is usually lost as high carbon content fly ash. The results of recent test programs related to combustion efficiency have demonstrated that a major portion of the heat loss in high carbon content fly ash can be recovered. When fly ash reinjection to a main cell is used, combustion efficiencies of over 96 percent are attainable. When fly ash is injected to a carbon burnup cell, combustion efficiencies over 99 percent can be expected. The fly ash characterization tests show that fly ash which will be used for reinjection should be selectively collected to minimize inerts reinjection. Theoretical calculations show that the carbon distribution in the fly ash will be affected by the operating superficial velocity as well as the combustor geometry.

SECTION 4.0

PRESSURIZED FLUIDIZED BED COMBUSTION (PFBC)

In 1969, testing began in Leatherhead, England to pressurize the fluidized bed in hopes of realizing greater advantages over conventional coal fired boilers. These tests were successful, and, as a result, programs aimed at developing this technology were initiated in the United States by DOE, EPA, and others.

Pressurizing the fluidized bed combustion process requires lock hoppers feed bins, pneumatic feeding devices, and lock hoppers ash extraction devices. Since the fluidizing medium is pressurized, a lower minimum fluidizing velocity is attainable, thus increasing gas residence time, improving sulfur capture, and increasing combustion efficiency to near 100 percent. With pressurization, the boiler volume is reduced compared to conventional boilers, as indicated in Figure 16.

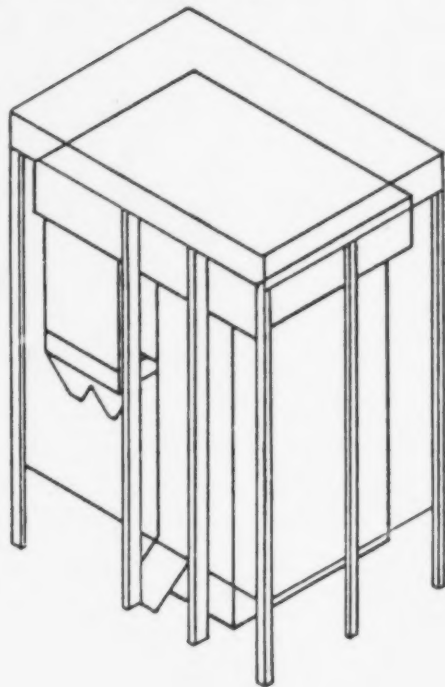
Atmospheric pressure fluidized beds as utility boilers have several advantages over conventional pulverized coal fired boilers, including a potential fivefold increase in heat transfer rate, low combustion temperatures and NO_x levels, toleration of a wide range of coal properties, and SO_2 removal. By pressurizing the combustor, additional advantages are realized, including higher heat transfer and volumetric heat release rates, (resulting in a smaller volume), fewer coal feed points, lower NO_x emissions, and improved SO_2 capture. A pressurized combustor can be applied to a combined cycle plant to take advantage of its inherent high efficiencies.

4.1 BACKGROUND

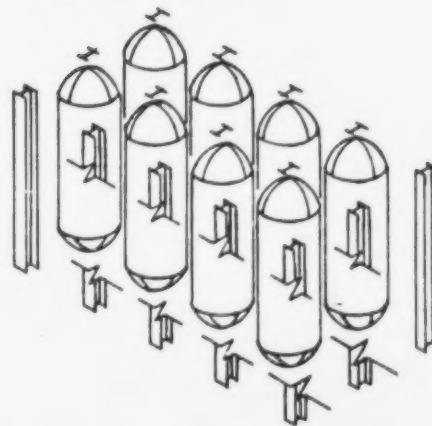
There are two basic PFB concepts under development in this country: steam cooled and air cooled bed designs. As shown in Figure 17, the

FIGURE 16
SIZE COMPARISON OF CONVENTIONAL AND
PRESSURIZED FLUIDIZED BED BOILER

660 MW
CONVENTIONAL BOILER

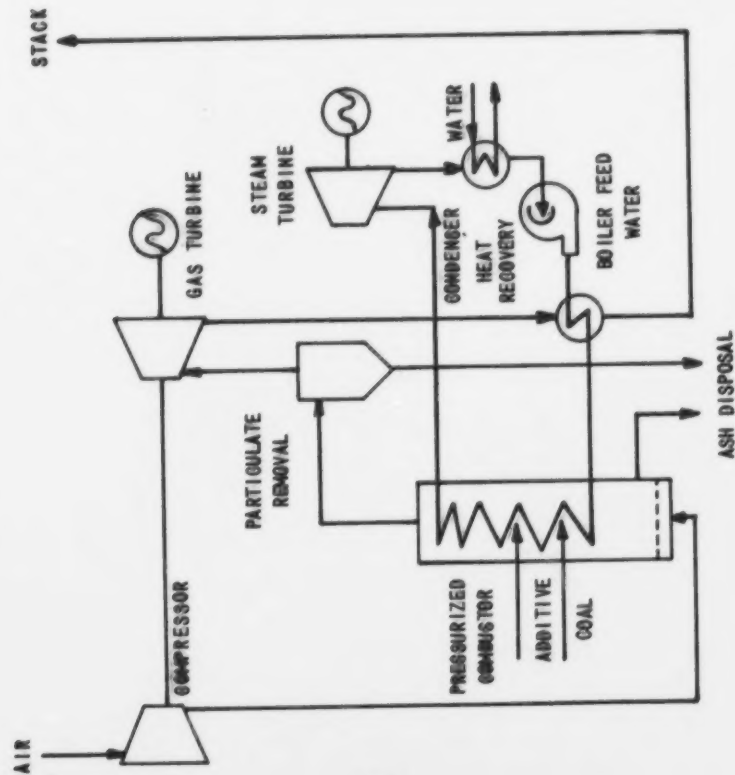


660 MW
PFB BOILER SYSTEM



0 50 100
SCALE IN FEET

PRESSURIZED STEAM-COOLED COMBUSTOR



PRESSURIZED AIR-COOLED COMBUSTOR

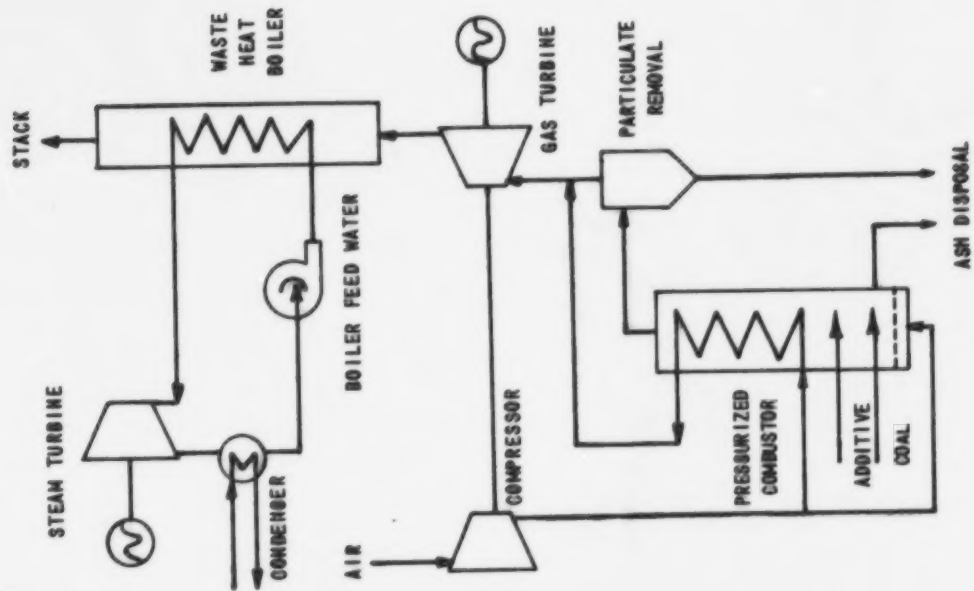


FIGURE 17
FLUIDIZED BED COMBUSTION SYSTEMS UNDER DEVELOPMENT

air cooled concept will rely on gas turbines for the majority of electrical power produced (60 percent), while the steam cooled concept provides most of its power (78 percent) from the steam turbines. Each concept has advantages, and which will be the most attractive from a technical and economic viewpoint has not yet been established. A third concept does not use cooling tubes in the bed but provides high excess air to control bed temperature; it is not being actively developed at this time. In each concept, air for combustion is supplied by a turbine driven compressor. Heat from coal combustion raises the bed and flue gas temperature to 1,550 to 1,750°F. This heat is removed from the bed by air or steam cooled heat exchanger tubes, and the steam drives a generator. After particulates are removed, the hot flue gas and hot air is expanded through a compressor turbine followed by a power turbine driving a generator to produce electric power. Sulfur dioxide (SO_2) is removed by a sorbent material injected into the combustor. A dry, stable calcium sulfate (CaSO_4) compound is produced which can be disposed of in a landfill.

Several conceptual designs of PFBC plants using variations of these concepts have been developed, and, although a considerable amount of PFB combustor operation has taken place, only a limited amount of operating time has been logged with a turbine following the combustor and gas cleanup devices. The fluidized bed effluent, by the nature of the process, contains a high concentration of particulates which must be removed prior to expansion in the turbine. Since no device is available commercially which will remove these particulates at the required temperature, hot gas particulate removal is a key technical issue which may be an obstacle to near term commercialization.

Another critical problem pertaining to hot gas cleanup is that of alkali metal removal, since measured alkali metal emissions are one to two orders of magnitude greater than those produced by the combustion

of residual oils in large industrial turbines. Suppressing or filtering the alkalis and/or developing turbine materials which will resist corrosion and sulfidation are under development. Deposition of particulate matter on turbine parts affects the performance of the turbine and may also contribute to the corrosion process.

One of the problems in characterizing particulate loadings from existing combustors is adequate measurement. State of the art impactor devices are not calibrated to the desired temperatures for accurate measurement. Measurement of alkali metal concentrations in the PFB effluent is even more difficult, and an adequate measuring tool must be developed.

Coal feeding is a major problem being addressed in several development programs. Plugging, coking, burning, and poor distribution between feed points are problems that have been identified in fluidized bed development programs and have caused shutdowns and maintenance problems. Curtiss-Wright has approached the problem of coal gun coking, plugging, and burning by designing an easily replaceable gun for their DOE-sponsored 13 Megawatt electric (MWe) pilot plant. Other development programs are addressing approaches to splitting and pumping coal flow streams to assure uniform feeding to each nozzle. Operating experience on technology rigs and pilot plants will be valuable in solving the coal feed problems.

Heat exchanger tubes within the bed must operate in a more severe environment than that of a conventional boiler. Even though the bed is cooler than the combustion zone of a conventional coal boiler, the tubes run hotter because of the exceptionally high heat flux. When the air cooled bed is used, the tube temperatures are even greater. However, many tests have indicated that an acceptable tube life is attainable.

The coal feeding and the tube material issues can probably be resolved in the present course of development. The greatest obstacle to PFBC development is cleaning the flue gas at temperatures and pressures to prevent harmful corrosion and erosion problems.

4.2 PFB PILOT PLANTS

Two pilot plants are now being designed and built with support from DOE. These are the International Energy Agency (IEA) and Curtiss-Wright (C-W) facilities of 25 and 13 MWe (equivalent) output, respectively. The IEA facility is supported by contributions from three countries, England, Germany, and the United States, while the C-W plant is supported by funds from the U.S. alone. The IEA facility at Grimethorpe, England is scheduled to start up in January 1980, and the C-W plant will seek approval for construction in September 1979. A third plant design of demonstration size has been studied and funded by American Electric Power (AEP). AEP is currently scheduled to begin detailed engineering of their 170 MWe plant in January 1980 and to start operation in January 1984. Supplemental funding from DOE or the EPRI may be sought, but the amount and terms are uncertain at this time. The AEP effort could speed commercialization of PFB technology. A comparison of the operating conditions of the three pilot plants is presented in Table 5.

4.2.1 Curtiss-Wright 13 MWe Pilot Plant^{58,59,60}

The center of the DOE PFB program is a cost-shared 13 MWe PFB pilot plant, being designed, constructed, and operated by the C-W Power Systems Division with Stone & Webster Engineering Corporation and Dorr-Oliver Corporation (a C-W subsidiary) as subcontractors. The program began March 1, 1976, with Phase I - Preliminary Engineering followed by Phase II - Pilot Plant Final Design.

TABLE 5
PFB PLANT COMPARISON

	<u>IEA</u>	<u>C-W</u>	<u>AEP</u>
Nominal Output, MWe (equivalent)	25	13	170
Combustor Type	Sq. furnace within cylindrical vessel	Cylindrical combustor vessel	Furnace within spherical vessel
Combustor Dimensions:			
Internal Dimensions, ft	6.5x6.5	12.33	-
Cross-sectional Area, ft ²	42.3	119.5	
Bed Depth, ft	10	16	12
Freeboard Height, ft			
No. of Coal Feed Points		12	36
Operating Characteristics (nominal)			
Coal flow, lb/hr	22,000		
Pressure, atm	10	7	16
Bed Temperature, °F	1,560	1,650	1,550
Fluidizing Velocity, ft/sec	8	2.7	3
Combustion airflow, lb/sec	68	40	
Cooling Tube Configuration	Horizontal Bayonet	Vertical	-
Cooling Medium	water/steam	air	water/steam
Excess Air, percent		30	100
Steam Conditions, psig °F			1,300/925
Gas Cleanup Train	2 cyclones	2 cyclones	
Integrated Gas Turbine	no	yes	yes

The overall objective of the pilot plant project is to engineer, design, construct, test, and evaluate a PFBC pilot plant using the Curtiss-Wright air heater cycle, burning five ton/hr of high sulfur coal for producing seven MWe in a 13 MWe industrial total energy system. Since the most obvious commercial application of the PFB combustor gas turbine cycle is based load electric utility power production, the pilot plant concept will serve as a scaled down model of a commercial plant module and will simulate operation of a commercial plant. To meet these objectives, the phased contract approach includes:

- 100 hp small gas turbine process development unit (SGT/PDU)
- 13 MWe (equivalent) pilot plant
- 480 MWe commercial plant concept study
- Supporting technology activities.

The phased work breakdown is:

- Phase I - Preliminary Engineering
- Phase II - Pilot Final Design
- Phase III - Pilot Plant Construction
- Phase IV - Pilot Operation, Maintenance, Testing, and Evaluation

A 2.3 Megawatt thermal (Mwt) PFB Technology Rig, designed and constructed during Phase I is providing support for the pilot plant design. The rig is the same as the pilot plant and commercial plant in the vertical dimension, i.e., bed height, freeboard height, heat exchanger tube length, etc. A description of the rig and associated programs is discussed in a later section.

The "air heater" cycle depicted in Figure 18 was chosen by Curtiss-Wright based on the advantage of "diluted" airflows supplied to the gas turbines, thus minimizing turbine wear due to erosive and

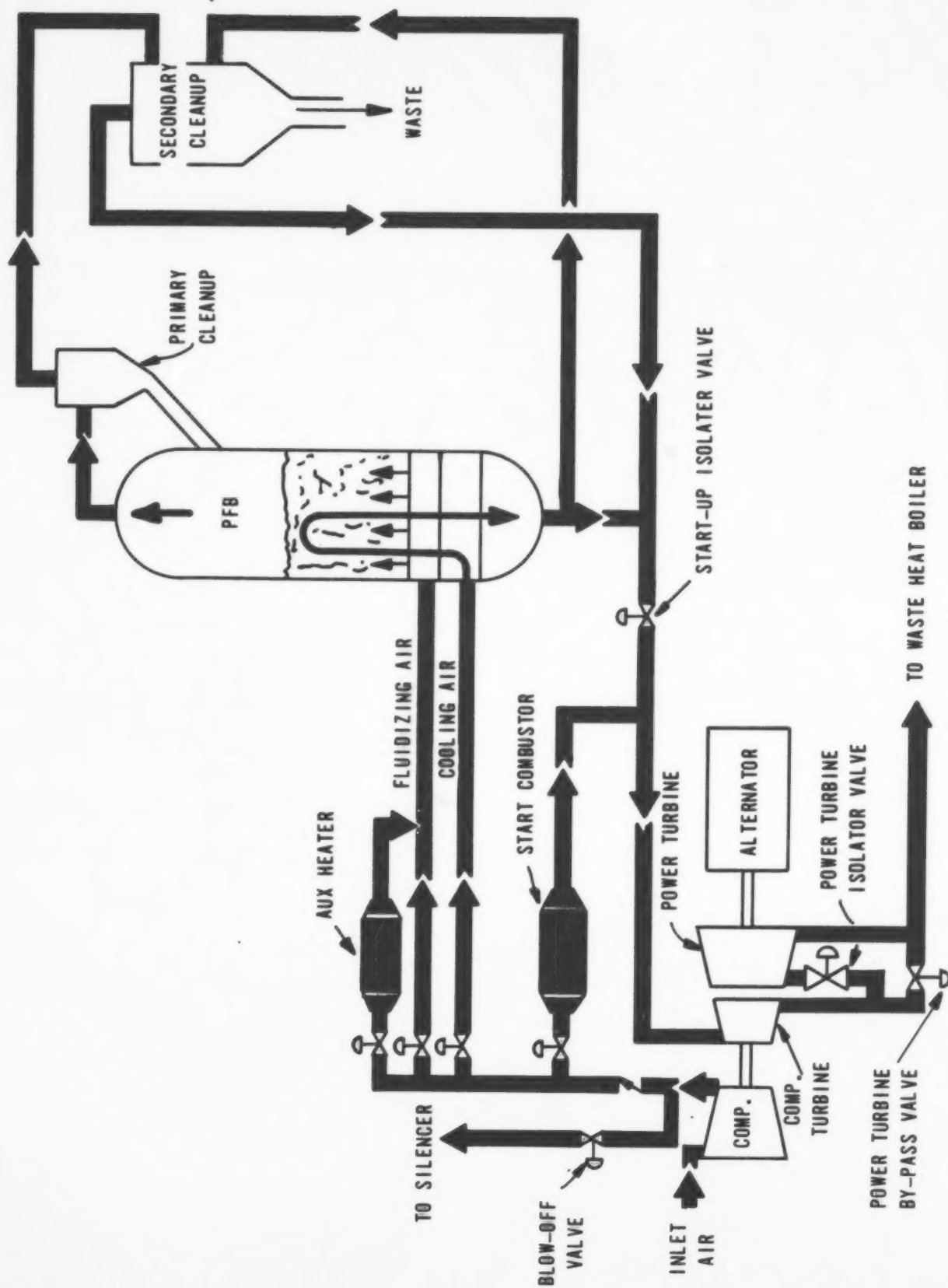


FIGURE 1R
CURTISS-WRIGHT PFBC PILOT PLANT SCHEMATIC

corrosive contaminants in the gas. Air from the J65 compressor at seven atm fluidizes the 16 ft bed where coal is burned to maintain the bed at 1,650⁰F. Dolomite, which is injected into the bed, combines with the sulfur in the coal. Spent dolomite and ash are withdrawn from the bed and cooled in a fluidized air column. At full power, two-thirds of the compressor air travels through vertical finned cooling tubes and is heated to 1,573⁰F. After the combustor air is cleaned, it recombines with the heated air and is expanded in the compressor turbine and further expanded through a free turbine driving an alternator. The air supplied to the turbine is "diluted" in the sense that one-third of the air flow is combustor air with some particulate and alkali metal contamination and two-thirds, heated indirectly by heat exchanger tubes buried in the bed, is free from contamination. Some system efficiency advantage for the air heater concept (vs. steam cooled) is claimed by C-W. They also claim that cooling tube leaks with the air heater process will not be as serious as in a steam cooled design. Limitations of the design include the requirement for significantly more heat transfer surface with air, due to the low air heat transfer coefficient.

The pilot plant combustor diameter is 44 percent and the turbine diameter is 42 percent of that proposed for the modular commercial plant. Vertical dimensions and tube spacing are identical. Steam from a waste heat boiler in the commercial plant will be used to drive a steam turbine/generator, whereas the pilot plant will only produce plant heating steam. In the commercial plant, 60 percent of plant output will be produced by gas turbines and the remaining 40 percent by steam turbines, as compared to the steam cooled concept, in which 22 percent is produced by gas turbines.

Phase I activities have been completed. Included in the technology support experiments of this phase were materials tests in lime calcining facilities provided by Dorr-Oliver clients. The environment is expected to be less severe in the PFB than in these test facilities.

Phase II is nearly complete. Several delays in SGT testing have had a negative impact on go-ahead decisions regarding the pilot plant. At the present time, vendors are proceeding with certified drawings to complete the design; however, purchase orders to begin construction (Phase III) have not been issued. SGT long term testing to verify Pilot Plant design parameters has not been completed. The hot gas cleaning issue is not resolved in the SGT, i.e., acceptable particulate loadings have not been demonstrated. As a result, the configuration which will be used in the pilot plant is not defined. Measures have been taken to provide for several contingencies in the pilot plant program. The installation of high temperature bag houses, electrostatic precipitators, and granular bed filters, as well as additional cyclones, have been considered for the pilot plant should one of these configurations prove more promising than the present design. Several contracts have been issued by DOE to develop these concepts, and an advanced device may be installed in the pilot plant. A "decoupling study" was completed by Gilbert/Commonwealth, which concluded that the turbine could be "decoupled" from the particulate laden PFB combustion gases, thus, providing a vehicle for testing somewhat unproven gas cleanup devices.

Although some preconstruction activities have been initiated, i.e., issuance of "engineering only" purchase orders to the vendors and some long-lead material orders, Phase III has not started, pending results of on-going SGT rig tests. Many issues have already been resolved in more than 900 hours of rig operation, including start-up requirements, controllability, uniform bed temperature, SO_2 and NO_x control, up to 900 hr on candidate heat exchanger materials, and adequate coal/dolomite feeding capability. The primary technical issue remaining is hot gas cleanup and its effect on turbine life. It is unlikely that construction will begin until an adequate demonstration of gas cleanup occurs.

Plans for the coming year will focus upon completion of the pilot plant final design, i.e. incorporating certified drawings into existing construction bid packages, initiation of construction activities, and a 20 month construction period. These activities will be dependent upon demonstration of adequate hot gas cleanup. The Institute of Gas Technology (IGT) technology rig operation will continue to provide data on tube materials, turbine materials, particulate measurement, and hot gas cleanup.

4.2.2 International Energy Agency - Grimethorpe Project
25 MWe Pilot Plant^{61,62}

The United States, United Kingdom, and Federal German Republic comprise the International Energy Agency (IEA), formed in 1974. In 1975, by agreement of the members, work began on the Grimethorpe Experimental Facility. The 25 MWe (equivalent) plant was scheduled for completion in early 1979 with experimentation to follow for an additional four years. The current schedule calls for start-up in January 1980 with performance testing to begin August 1, 1980. The agreement provides for the following four principal stages in the program over the period of seven years during which the experimental stage provides the most important objective.

- Stage 1 - Procurement of the design study with accompanying documents.
- Stage 2 - Tendering for the construction plant and appraisal of tenders.
- Stage 3 - Construction and acceptance of plant.
- Stage 4 - Operation of the plant.

The major part of the work is now in Stage 3. Broadly, the objectives of the program are threefold:

- Objective 1 - To build the experimental facility to study combustion, heat transfer, gas cleanup, corrosion, and energy recovery in a pressurized fluidized bed combustion system.
- Objective 2 - To carry out tests over a wide range of operating conditions and to make measurements in greater detail than would be either economic or possible in a totally integrated unit.
- Objective 3 - To provide data for the analytical modeling of design data for larger commercial plants by empirical data extrapolation.

The experimental facility provides the means to conduct research into a number of aspects of large commercial plants, and in the immediate future, the following studies will be conducted:

- Combustion performance using high ash coal.
- Effects of dolomite additives on sulphur retention.
- Study of heat transfer coefficients, heat transfer element materials, and geometry.
- Gas cleanup and dust removal prior to atmospheric discharge.
- Flue gas corrosion and particulate erosion effects upon gas turbine blade materials, leading to the optimization of a flue gas driven gas turbine design.

The facility, as shown in Figure 19, consists principally of the combustor which is coal fueled from a coal/dolomite crushing and blending plant. The combustor steam generation powers a turbo-compressor pressuring the combustion system. The steam is condensed, and the condensate is processed to the required water quality before return to the steam water circuit.

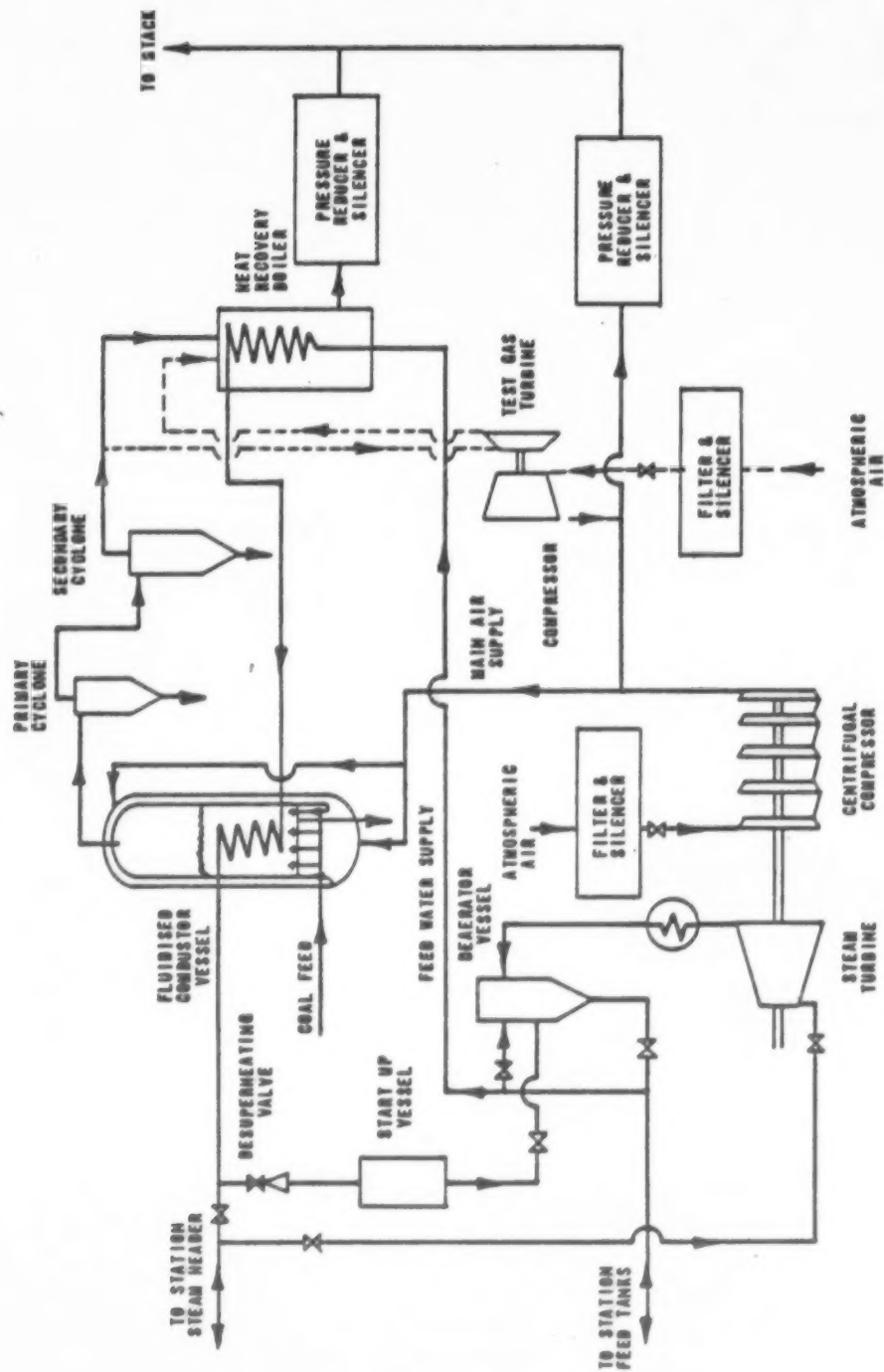


FIGURE 19
 FLUIDIZED BED COMBUSTION
 DIAGRAMMATIC FLOW SHEET
 OF THE GRIMETHORPE EXPERIMENTAL FACILITY

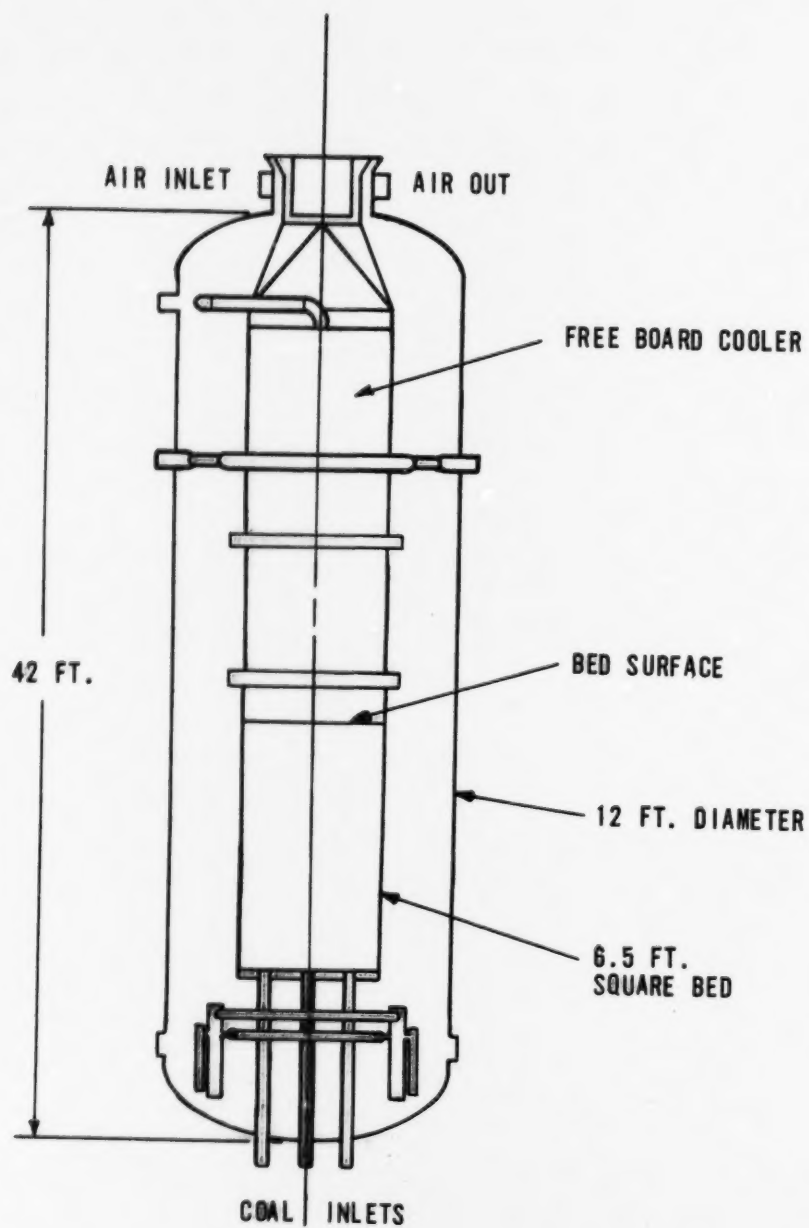
The facility will not be fully integrated, i.e., initially there will be no gas turbine supplying electric power; however, a steam turbine fed by steam raised in the combustor heat exchanger will supply compressed air for combustion. The plant is flexible, as the steam circuit interfaces with the power station for import or export of steam, as required by the desired operation mode.

Off-gas from the combustor is cleaned of entrained particulate matter by passage through two cyclone stages, before cooling, pressure let down, and discharge to the atmosphere through a silencer and stack. Ash disposal from the combustor and gas cleaning system is provided by suitable batch hold and dumping facilities.

Coal is crushed on-site to a wide range of sizes and dried in a fluidized bed drier to less than one percent moisture. A 640 ton dolomite storage silo will be supplied with pre-prepared material delivered by truck. Space has been left in the layout for a 20 ton additive silo which will be similarly supplied with pre-prepared material. A blending system, integral with and supplied by the above storage system, functions to permit batch mixing of coal, dolomite, and additives to any proportion required by the experimental facility. The blender is equipped with weighing hoppers sensed by strain gauges, delivery control valves, and the necessary control system coordinated by a microprocessor unit. The blend will be delivered to the fuel injection assembly. The fuel injection system was designed and built by Petrocarb and uses pneumatic dense phase transport. An inclined screw conveyor system will extract ash from the combustor.

The 120 ton combustor, built by Vereinigte Kesselwerke AG (VKW), has been delivered to the construction site. It consists of a furnace within a pressure shell. The pressure shell, designed to operate at a maximum pressure of 15 bar and butt welded together, was subcontracted by VKW to Borsig in Berlin. As shown in Figure 20, the cylindrical shell is terminated by domed ends, of which the upper is welded to the

FIGURE 20
GRIMETHORPE
COMBUSTOR PRESSURE VESSEL



shell, and the lower is flange fitted permitting removal and ready interior access for inspection, adjustment, and removal of the combustor internals during shutdown. The upper pressure shell dome is integral, and a refractory lined hood removes flue gas from the combustor. The pressurized fluidizing air intake is to the annulus between the hood and the main pressure shell. At the lower end, the hood is connected to the upper end of the furnace water-wall. The lower pressure-shell dome carries the pipework penetrations for the fluidized bed services such as fuel feed, bed material, and ash disposal. The furnace contained within the pressure shell is of square cross section 2m x 2m, the walls of which are constructed as water walls consisting of spiral tubes (38 mm outer diameter x 4.5mm wall). The water walls, in addition to absorbing heat, contain the fluidized bed and the resulting hot gas stream. The upper connection is to the insulated hood and gas outlet as previously described.

The distributor plate provides the floor of the fluidized bed and accommodates the fuel injection nozzles, the fluidizing air distribution system, ash removal, and bed material supply. To date, two distributor plates have been designed and provide for differing numbers of fuel feed points. The distributor plates are capable of positioning at three specific levels relative to the tube bank. The first distribution plate, 1.32m x 1.96m, is a double plate that sandwiches a pattern of vertical baffles dividing the space into the nine even size compartments. Propane feed to these compartments provides the bed ignition to any required pattern. The plate supports nine fuel feed nozzles perforating the plate and is designed to uniformly supply the bed without risk of plugging during operation. The nozzles are obliquely truncated short horizontal pipes. Bubble caps also perforate the plate and are designed and arranged to ensure complete fluidization of the bed without risk of partial collapse or nonfluidized zones. The bubble caps are fed from the primary pressurizing air supply to the combustor. Distributor plate number two is constructed in the same manner as one but provides for four coal

feed nozzles. Thus, both the first and second distribution plates provide for a range of coal feed rates and supply patterns requiring study during the experimental program.

Heat transfer from both the combustion zone and the off-gas is undertaken by a number of horizontally oriented tube bundles designed to present the necessary surface area for required duty with the minimum disturbance of the in-bed flow patterns necessary for efficient operation. All of the heat transfer tube bundles installed in the combustor, heat exchanger, and auxiliary heat exchanger are connected to complete the steam water circuit. This circuit provides the steam to drive the turbocompressor and also exports steam to the power station.

Hot gas cleanup will be achieved by four primary and four secondary cyclones. Future plans include the installation of a tertiary cleanup system and gas turbine.

The start-up date has been changed from early 1979 to January 1980, with the test program to begin six months later. Commissioning of some parts of the plant has begun.

A test program consisting of the following three test series will begin in August 1980:

- Performance testing
- Process variable parametric tests
- Combustion of alternate coals.

4.2.3 Engineering Development System (EDS)⁴⁹

American Electric Power Service Corporation (AEP), Stal-Laval Turbin AB (SL) of Sweden and Babcock & Wilcox, Ltd. (BWL) of Great Britain initiated a joint research and development venture in December 1976 to

evaluate the practicality pressurized fluidized bed combustion to generate electric power. The purpose of this venture was to evaluate the technical and economic feasibility of burning high sulfur coal without recourse to stack gas scrubbing.

The evaluation of PFBC for electric power generation is being studied in the course of designing a large scale Engineering Development Systems (EDS) plant parallel with a technology development program.

Pioneering work on PFBC has been conducted in Great Britain since the mid-1960s by the National Coal Board's Coal Utilization Research Laboratories (CURL) at Leatherhead, England. SL and BWL have had access to this data and have been collaborating in the development of PFBC since 1974 utilizing SL's GT-120 gas turbine as the basic power generating unit.

The consolidation of a coal-burning GT-120 with a steam turbine will be performed at the Tidd Plant of the Ohio Power Company (an AEP System Company), located on the Ohio River at Brilliant, Ohio. The Tidd Plant presently consists of two 110 MWe pulverized coal fired generating units. For the 170 MWe PFBC facility, AEP intends to replace one of the Tidd units with a 65 MWe GT-120 gas turbine to be used in conjunction with the other unit in a combined cycle operation.

The 170 MWe PFBC thermodynamic cycle is illustrated in a simplified form by Figure 21. The PFBC combustor is supplied with air derived from the high pressure (HP) compressor and is supplied with coal and dolomite by a Petrocarb feed system which is not shown. The combustor is cooled by means of a steam tube bundle positioned within the fluid bed. The steam produced in the fluid bed is conveyed to the existing Tidd steam turbine. This turbine is 1940 vintage so the steam conditions are modest by today's standards. The steam flow rate is 860,300 lb/hr at 1,300 psia and 925°F. The steam expands through the

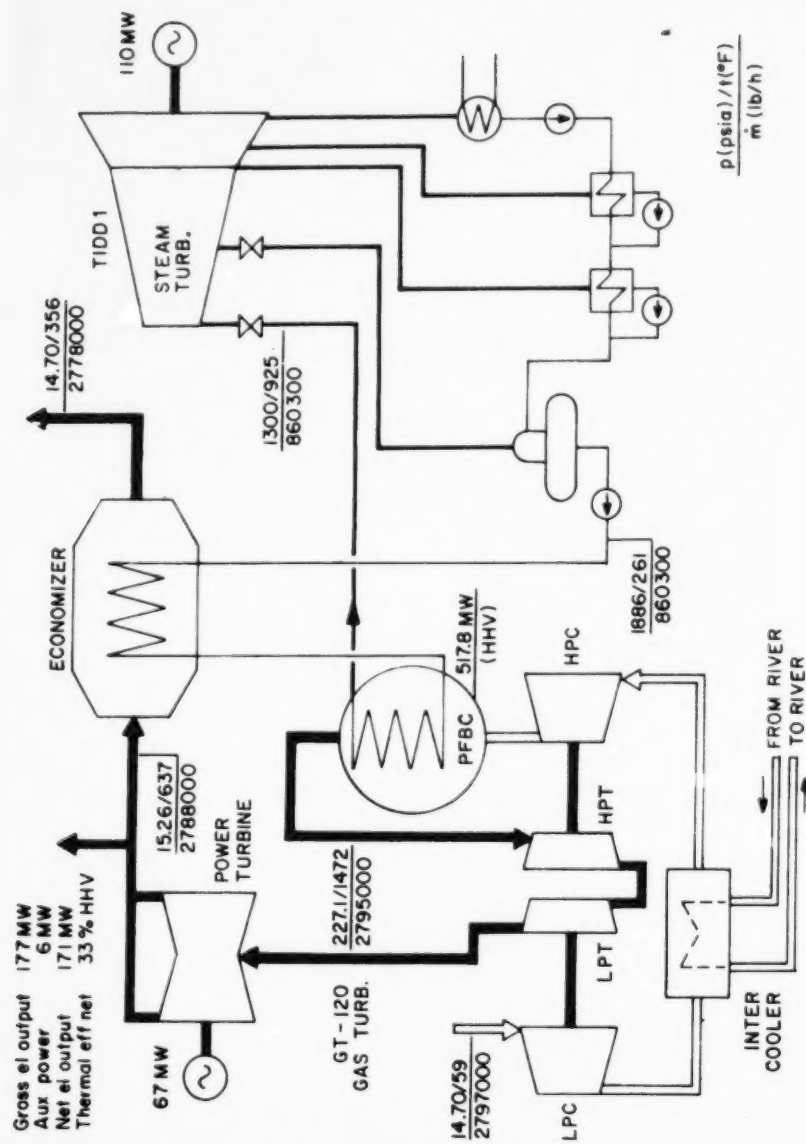


FIGURE 21
AEP/STAL-LAVAL TIDD PLANT
170 MW PRESSURIZED FLUIDIZED BED COMBUSTION (PFBC) SYSTEM SCHEMATIC

single shaft turbine and produces 110 MWe. The condenser operates on a once through circulating cooling water principle, and extracts heat from the expanded steam at 1.5 in. Hga.

Feedwater is returned to the evaporator section of the boiler through the two stages of closed extraction feedwater heating and a single stage of open feedwater heating. A new stack gas economizer, recovering waste heat from the power turbine exhaust is in series with the existing extraction feedwater heaters.

The PFBC combustion temperature is maintained at 1,550°F with combustion air flow and steam generation. Hot combustion gases at this temperature leave the fluidized bed at a velocity of three ft/sec and pass through three stages of cyclones. These cyclones are located within the PFBC vessel. The gases leave the combustor vessel via two coaxial pipes that connect the combustor vessel to the HP turbine casing. The gases expand through the high and low pressure turbines and the power turbine where 67 MWe is generated.

The net plant power output is 17 MWe, the in-plant auxiliary power requirement six MWe. The coal pile to busbar thermodynamic efficiency is expected to be 33 percent. The original thermodynamic efficiency for the Tidd plant was only 31 percent. The combined cycle application increases the net overall efficiency by two percentage points over the original thermodynamic efficiency for the Tidd plant.

The design parameters are listed in Table 6. The sorbent requirements were selected to meet 90 percent sulfur removal. The design combustion efficiency is 99 percent. The low fluidization velocity of three ft/sec and the deep 12 ft bed result in conditions highly favorable to efficient combustion and sulfur capture.

TABLE 6

DESIGN PARAMETERS PFBC DEMONSTRATION PLANT

	<u>PHASE IV</u>
POWER OUTPUT MWe - NET	170
COAL (TONS / HR.)	89
SORBENT (BASED ON 4% S) DOLOMITE (TONS / HR.)	29
PLANT EFFICIENCY (%) - NET	33
GAS TURBINE	
INLET TEMPERATURE (°F)	1470
INLET PRESSURE (PSIA)	210
GAS FLOW (Lbm/HR.)	2.92×10^6
STEAM TURBINE	
INLET TEMPERATURE (°F)	925
INLET PRESSURE (PSIA)	1300
STEAM FLOW (Lbm/HR.)	8.6×10^5
PFBC COMBUSTOR	
OPERATING PRESSURE (PSIA)	223
BED TEMPERATURE (°F)	1550
FLUIDIZATION VELOCITY (FPS)	3
COAL AND SORBENT SIZE (INCHES)	$1/8" - 0$
BED DEPTH (FT.)	12

The project has been divided into several distinct phases. Phase I consisted of a feasibility study which used preliminary design based on a 170 MWe combined cycle development plant. This preliminary design would be the model for the projected first commercial plant. A confidential PFBC Program Feasibility Study Report, produced in June 1977, was sufficiently encouraging to justify proceeding with the next phase of the project.

This next phase entailed running a series of combustion tests, using Ohio high sulfur coal and dolomite at the CURL facility. The combustion test program was comprised of five 25 hour screening tests and two 100 hour tests in the PFBC pilot plant. The purpose of the test program was to: 1) determine the sulfur capture efficiency of three sorbents, limestone, dolomite/limestone, and pure dolomite; 2) obtain performance data from a PFBC pilot plant operating on the selected coal and dolomite, including part load bed dynamics, combustion efficiency, sulfur retention, NO_x emission, and particulate loading; and 3) assess the corrosion/deposition/erosion of a set of GT-120 blades subjected to PFBC gases. This test program was completed in July 1978.

The partners mutually decided that AEP and SL will continue their direct involvement in future phases, with BWL indirectly supporting the project as a subcontractor to SL for certain aspects of the engineering and design of the combustion equipment.

Phase II began in September 1978 and is a one year effort comprising two parts running in parallel. Phase II-A will include cold and hot tests and development and validation of analytical models to quantify crucial design items and finalize the design basis for the combustor. The cold model tests will study fluidization of various bed configurations to select the optimum configuration.

Phase II-B is an engineering design effort in which the theoretical studies and testwork will continue with the 170 MWe preliminary plant design to refine the cost estimate. A preliminary design and cost estimate will also be performed for the proposed 500 MWe commercial plant. The intent is to compare this plant to a comparable size conventional plant using FGD.

Phase III beginning in January 1980 will include completion of detailed engineering, purchase of all equipment items required for the later conversion of the Tidd plant to combined cycle operation, including maintenance and rehabilitation, erection of plant, and start-up of the first stage in 1984.

The first stage is a simple cycle consisting of a gas turbine operating in conjunction with an open or adiabatic bed. The second stage is an extension of the first which adds the steam turbine cycle to complete the combined cycle plant.

The combined cycle output of 170 MWe which is larger than any other PFBC scheme being considered. The construction and development of equipment representing new technology has been kept to a minimum.

After start-up of the simple cycle and a suitable test program, the development plant will be modified to the combined cycle mode for operating in late 1984.

After conversion to combined cycle, the plant will be subjected to a comprehensive test program to establish whether it meets anticipated performance goals relating to emission standards, dolomite consumption, and power output. Testing of gas turbine and boiler tube materials and hot gas cleanup is also being considered. Data obtained during this phase will be used to design a PFBC commercial plant.

4.3 PFB TECHNOLOGY RIGS

There are six technology rigs which are being or have been operated by the DOE, RPA, or NASA. The Coal Utilization Research Laboratory (CURL) rig, operated by the National Coal Board, has been in operation for ten years, the longest, and the Curtiss-Wright (C-W) rig, the most recent addition, has been operating for over one year. All of the rigs are currently active with the exception of the CPC nine Mwt rig, which is not expected to be used again. The active units described in this section range in size from 0.1 Mwt (Argonne National Labs) to 2.3 Mwt (C-W). A description of rig operating conditions is given in Table 7, and a layout of the combustors of the five active rigs is shown in Figure 22. The nominal operating conditions of the rigs do not always correspond with the size of the rig. Operating conditions could be changed somewhat, since the rigs are not integrated with boilers or turbines but are connected to plant air and water supplies. Thus, the rigs lend themselves to parametric analysis, and, because of their small size, are a proving ground for component materials, exhaust cleanup equipment, etc., in relatively inexpensive tests. Following is a brief description of the rigs, their place in the PFB Program, the accomplishments to date, and the plans for upcoming tests.

4.3.1 CURL 1.8 Mwt Technology Rig^{63,64}

Testing began in 1969 at the 1.8 Mwt Coal Utilization Research Laboratories (CURL) facility and provided a basis for PFB designs in this country with more than 1,500 hours of testing with coal. As a result of successful parametric tests conducted by CURL, an ambitious program has been undertaken by DOE to capitalize on the sulfur capture characteristics as well as the heat flow capabilities of PFBs. Prior to 1972, the combustor was operated for over 1,000 hours at 1,470°F bed temperature and was then modified to perform a series of parametric tests for DOE at higher bed temperatures. That series compiled over 500 additional hours, and, currently, another 1,000 hour tests is in

TABLE 7
COMPARISON OF PFB RIGS

	CURL	EXXON	CPC	ANL	C-W	NASA
Combustor Type:						
Combustor Dimensions size, ft ²	2 x 3	1 dia	7 dia	0.5 dia	3 dia	0.67 dia
cross sectional area, ft ²	6	0.79	39.4	0.2	7.1	0.35
bed depth, ft	8	14	2	3.0	16	4.0
freeboard height, ft	9	15		5.5	12	3.0
Operating Characteristics (nominal)*						
coal flow, pph	550	480	2,000	25	586	50
pressurization, atm	5	9	4	8	6.4	5.4
bed temperature, °F	1,650	1,700	1,550	1,550	16.50	1,600
fluidizing velocity, fps	2.5	6	4	3.5	2.7	4.5
combustion air flow, pps	1.7	.72 - .92	22.7	0.11	2.3	0.17
tube configuration	Horizontal	Horizontal	None	Vertical hairpin	Vertical bayonet	Horizontal
cooling medium	Water	Water	None	Water	Air	Water
excess air, %	20	20	200	44	30	
Gas Cleanup Train	3 cyclones	3 cyclones	2 cyclones	2 cyclones	4 cyclones	2 cyclones
Rotating Turbine	No	No	No	No	Yes	Yes

*Note that nominal conditions do not represent the capacity of the rig. Capacity (or potential) is probably best indicated by the cross sectional area of the bed.

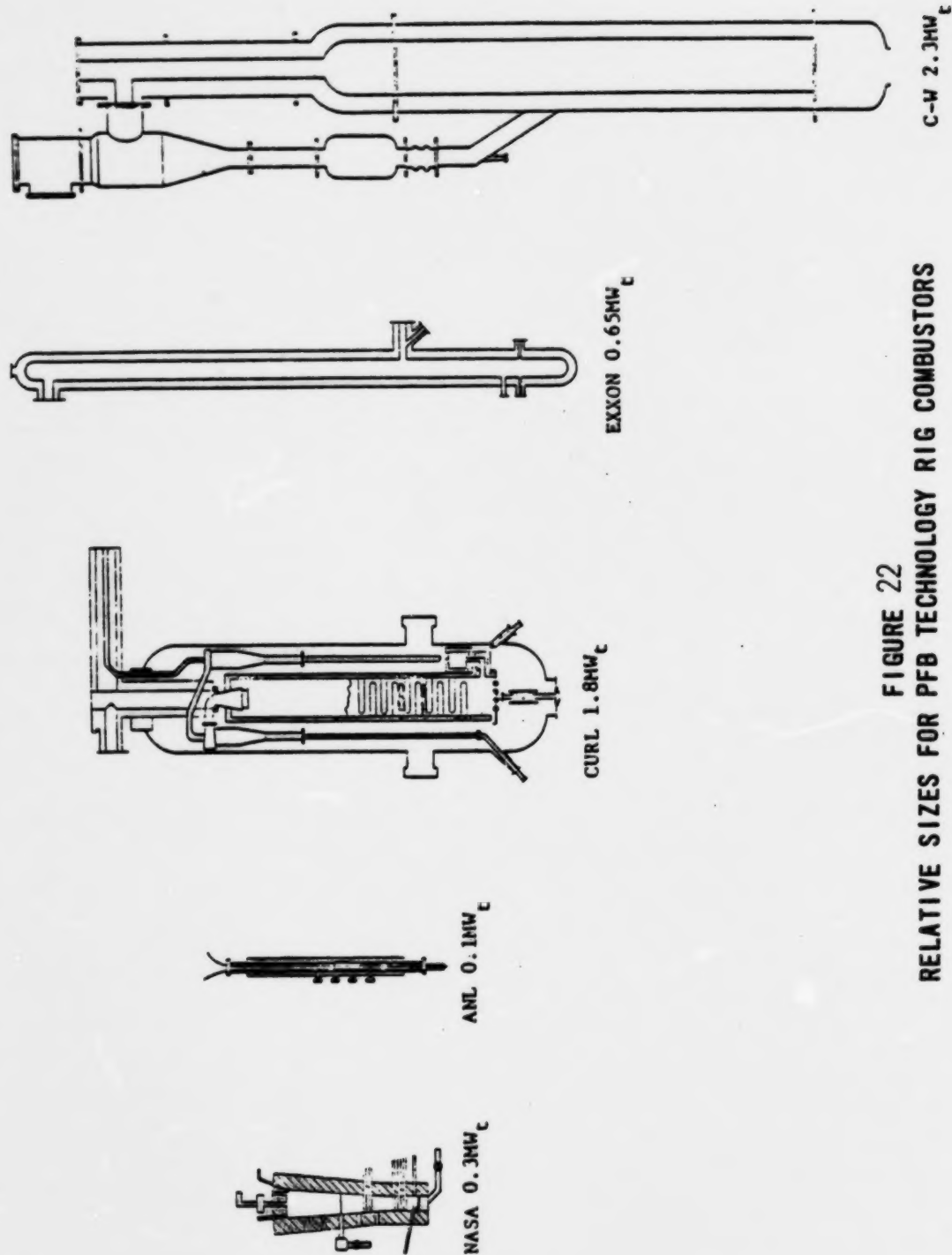


FIGURE 22
RELATIVE SIZES FOR PFB TECHNOLOGY RIG COMBUSTORS

progress. At one point, the combustor was modified to accommodate deep bed tests (eight ft vs four ft) and has since used the eight foot configuration.

The refractory lined combustor of two ft x three ft rectangular cross-section, is enclosed in a six ft INNER DIAMETER. pressure vessel. Thus, the significant pressure differential is not taken across the combustor walls but across the vessel. Air enters the vessel through the top, flows around the combustor, and upward through the distributor plate and bed. In the bed, the air is heated by combustion of coal at 1,450 to 1,750⁰F. Heat is removed from the bed by 28 rows of horizontal water cooled coils. Two rows of closely pitched cooled "baffle" tubes are located 21 inches above the bed to assist in reducing elutriation. Situated above these tubes are freeboard cooling coils designed to lower freeboard temperatures, if necessary. Exhaust from the combustor passes through a diagnostic/sampling section and subsequently is cooled by water sprays. At higher than nominal fluidizing velocities, some gas bypasses this section. Coal from the storage and feed vessels (located on load cells) is split into six streams (two are spares) and fed to the bed through four nozzles. Dolomite is fed separately through a single nozzle. The CURL facility plays an important part in the DOE PFB program, since it is a basis for all existing PFB rigs and continues to be a dependable and available unit for turbine/tube materials, combustion, gas cleanup, and instrumentation tests. The rectangular bed, horizontal tube configuration is a design aspect that adds another dimension to the program.

As mentioned previously, this facility has provided a strong base for other PFB designs, both U.S. and British. Among the findings of the test program were:

- Combustion efficiencies were in excess of 99 percent at bed temperatures of 1,680 and 1,750⁰F without recycle.
- Sulfur emissions can be limited to 0.1 lb/million Btu by adding dolomite to give a Ca/S ratio of 2.
- NO_x emissions were held to 0.2 lb/million Btu on the average, and lower values could be achieved via lower excess air levels.
- Deposition of particulate materials may be a problem causing fouling and corrosion of turbine parts.
- The ash did not sinter or adhere to the combustor walls under any of the operating conditions investigated.
- Corrosion of in-bed components should not be a problem.
- Anticipated high heat transfer rates were verified.
- An increase in bed depth from four to eight feet did not significantly improve sulfur capture or combustion efficiency.
- Operation at seven ft/sec fluidizing velocity (vs 2.5 ft/sec) lowered combustion efficiency to 98 percent, as coal distribution is more critical.
- The PFB is capable of running within a wide range of operating parameters, as demonstrated by the series of test.

The problems which remain are hot gas cleanup and long term materials tests, for which the CURL rig can be utilized. Conceptual designs for larger plants, such as the American Electric Power (AEP) 170 MWe design will use the rig to test the specific design coal, dolomite, and

operating conditions. The rig is sufficiently proven and reliable to perform these functions in a timely fashion.

Planned activities include test support for the combined design venture of AEP and Stal-Laval of Sweden to build a 170 MWe PFB facility in Ohio. They are in the midst of a 1,000 hour test to investigate the behavior of Ohio coal and certain dolomites under a variety of operating conditions. Both in-bed and turbine cascade materials will be tested in this series.

4.3.2 Combustion Power Company, 9 MWt Technology Rig

Funded by EPA, Combustion Power Company (CPC) has constructed and operated a 9 MWt PFBC process development unit (PDU) designed to burn municipal refuse. Later, a contract was issued by ERDA (now DOE) to burn coal and to develop a granular bed filter (GBF) for hot gas cleanup. This was the first "integrated" PFB system, since a gas turbine was installed to provide process air by expanding pressurized flue gas. Initial operation with municipal refuse proved unsuccessful; long term operation was not achieved due to gas turbine fouling. Subsequent operation with coal also resulted in turbine fouling problems in addition to third stage multiclone plugging. A granular bed filter failure in 1976 caused a redirection of the program toward cold and hot rig testing and resulted in a shutdown of the PFB portion of the facility. Currently, there are no plans by DOE to reactivate the PFB unit, and work is continuing only on the GBF.

The CPC system is comprised of a coal processing system, a turboelectric generator system, a four atmosphere fluidized bed combustor, a hot gas cleanup system, a process control system, and an instrumentation system.

The coal processing system contains equipment for reducing the coal lump size to less than 1/4 inch and moving it to storage; for moving the SO₂-suppressing additive to storage; for providing dust control while processing; for providing an inert atmosphere while in storage; and for metering and pneumatically transporting the coal and additive to the fluid bed combustor in the correct portions and at the correct rate.

The combustor, 22 ft long and 9 1/2 ft in diameter, is a cylindrical carbon steel pressure vessel with dished heads. Since the upper chamber is exposed to high temperature gases, it is lined with refractory insulation. The cylindrical wall insulation consists of a hard, wear-resistant firebrick inner liner backed up with a liner of insulation brick. A thin layer of packed bulk kaowool insulation between the brick and the pressure shell isolates the shell from stresses induced by the thermal expansion of the refractory brick. The two-foot deep fluid bed is supported by a flat carbon steel plate insulated by two layers of castable refractories.

The particle separator system underwent several changes during the course of testing. A cyclone train, consisting of cyclones and multiclones, or a combination of cyclones and a granular bed filter was used for the final test.

The turbogenerator system consists of equipment components used in the delivery of compressed air for combustion of oil fuel or coal, the generation of electricity from the resulting hot compressed gas, and dissipation of the generated electric power. Major components of this system include the Ruston Model TA-1500 gas turbine with relocated Ruston combustor, a 1,000-kW ac generator, electric power switch gear, an electrical load bank, and load bank switching equipment.

The process control system interacts with the other systems to control their respective outputs in response to commanded set points, supervises the acquisition of data from various instrumentation channels, and reduces the data into a form suitable for test evaluation. The process control system includes both a manual control system and a computer (automatic) control system. The automatic control system is the primary control mode.

The instrumentation system includes data acquisition, exhaust gas analysis, particle analysis, and devices for monitoring system parameters (temperatures, pressures, speeds, rates, valve positions, etc.)

One limitation of the rig is the lack of flexibility of the combustor. There is no capability for installing cooling tubes; therefore, the bed is restricted to operation in an adiabatic mode requiring 300 percent excess air and a large bed cross-sectional area. The PFBC concepts which employ steam or air tubes to cool the bed are being actively developed within the DOE program instead of the adiabatic concept.

After nearly 600 hours of operation on coal, the following conclusions were formed:

1. Sulfur suppression of 95 percent and combustion efficiency of 99 percent are attainable at 1,600°F and Ca/S ratio of 1.5.
2. NO_x emissions are well below the EPA standard of 0.7 lb/10⁶ Btu.
3. At 300 percent excess air and burning 4 percent sulfur coal, SO₂ emissions can be suppressed to 0.6 lb/10⁶ Btu with a Ca/S ratio of 1.75.

4. The PDU has excellent controllability when operating on coal. Computerized "hands-off" operation will maintain bed temperature within $\pm 10^{\circ}\text{F}$ of the setpoint, and the turbine inlet temperature within $\pm 4^{\circ}\text{F}$ of the setpoint.
5. Cyclone separators are ineffective to reduce exhaust loading below $2 \text{ lb}/10^6 \text{ Btu}$ since about 50 percent of the particulate in the exhaust stream is smaller than 2 microns.
6. Multitube reverseflow inertial separators (3 1/2 in. and 6 in.) will not operate in a coal burning system without plugging because of the stickiness of the potassium and calcium compounds in the ash.
7. The combination of high loading of small diameter particles, agglomeration of small particles, and spalling of such agglomerations upstream of the turbine causes excessive erosion of turbine and turbine blades.
8. Temperature was shown to be the single most important factor in determining whether or not sulfidation will occur in a coal burning system.

Currently, the CPC PDU is intact; however, there are no plans by DOE to reactivate the unit. CPC is developing AFBC technology in-house and is currently active in AFBC lignite testing. They have sold two large AFBC units (18-24 ft outer diameter) which combust log fuel to operate a dryer or produce process steam.

4.3.3 Exxon 0.65 MWt Technology Rig 50, 51, 52

Exxon Research and Engineering has designed, constructed and is operating a PFB mini-plant under an EPA contract. The mini-plant

started up in February 1974 and has operated for a total of over 3,500 hours in a series of individual runs up to 240 hours in duration.

The major system components of the mini-plant include: 1) solids feeding, 2) combustor with internal subcomponents, 3) combustor cyclones, and 4) pressure control and flue gas discharge system. In addition, a sorbent regeneration reactor was integrated into the mini-plant in 1976.

Major deviations for this unit from a commercial unit include the absences of a gas turbine (pressure reduction is accomplished in an orifice) and a steam turbine cycle (steam is condensed and recycled to boiler). The unit also does not have a sulfur recovery operation. In addition, since feeds are purchased pre-sized and in bags, no fuel or sorbent preparation operations are located on site. For the commercial unit employing sorbent regeneration, the coal will serve as both regenerator and main fuel. The mini-plant currently employs natural gas to fire the generator.

The Exxon mini-plant combustor is a 32 ft tall vessel with a 24 inch shell refractory lined to a 13 inch inside diameter. Main fluidizing air for the combustor is supplied at pressures to 10 atm and controlled flow rates of 600 to 1,200 SCFM. Coal and sorbent are proportioned, premixed, and continuously pneumatically injected into the combustor at a side port 11 inches above the distributor grid. The air passes up through the distributing grid where it fluidizes the bed material and provides the air required for combustion.

Heat extraction in the combustor is achieved by cooling coils through which water is circulated. The coils are mounted on flanges and immersed in the fluidized bed. The coils are 1/2 inch pipe of 316 ss and are arranged in a serpentine, vertical orientation. Each coil consists of 5.9 ft² of surface area; the number of coils used can be varied from one to 10.

Flue gas exits the combustor and discharges through two stages of cyclones for solids removal. The solids collected by the first stage cyclone are returned to the combustor 20 inches above the grid. Solids, mainly fly ash, collected in the second cyclone are discarded by means of a lock hopper system. The expanded bed height is controlled by continuously rejecting solids through a port at the 90 inch elevation.

Discharge gases from the second cyclone enter a particulate clean-up vessel containing granular bed filters. These filters remove the final particulate before the flue gases enter the turbine test section.

The Exxon mini-plant has provided much of the data base for pressurized bed combustion. Major test programs carried out have included combustion studies, sorbent regenerator evaluation, granular bed filter evaluation, comprehensive analysis of emission, and corrosion and erosion materials testing.

4.3.3.1 Combustion Studies

Once-through carbon combustion efficiency in a PFBC ranges from 93 to 97 percent as the excess air level increases from 20 to 100 percent. An increase in the combustion efficiency to the target level of 98.5 to 99 percent was achieved with the recycle of carbon fines from the first stage cyclone to the combustor. Carbon combustion efficiency results were satisfactorily correlated using multiple regression. Temperature and excess air were shown to be the most significant variables.

The pressurized fluidized bed combustion (FBC) process is capable of meeting the EPA standards for SO_2 and NO_x emissions. A preliminary assessment of sorbent requirements based on data available to date indicates that the use of limestone will require a calcium-to-sulfur molar ratio of about 2.0 to 3.0 while dolomite use will require a calcium-to-sulfur ratio of about 1.0 to 1.5.

The NO_x emissions vary from 50 to 200 ppm or 0.1 to 0.4 lb/10⁶ Btu. The primary variable affecting NO_x emission is excess air (O_2 content in the flue gas). Temperature over the range of 1,250 to 1,750°F has a secondary effect. The emissions are well below the EPA new source performance standard of 0.6 lb/10⁶ Btu and have an average value of 0.2 lb/10⁶ Btu at 15 percent excess air, the level most likely to be used in commercial practice.

It is possible, with the two stage cyclone separator system used on the Exxon units, to reduce particulate emissions to the range of 0.2 to 0.4 gr/SCF. This is equivalent to 0.4 to 0.8 lb/10⁶ Btu and exceeds the emission standard of 0.1 lb/10⁶ Btu. However, even with improved cyclones, a third stage particulate removal device will be required to meet emission standards. The device will require a removal efficiency in the range of 75 to more than 99 percent.

4.3.3.2 Regeneration Studies

The regenerator consists of a refractory lined vessel with an inside diameter of 8.5 in and an overall height of 22 ft. Gaseous fuel is burned in a plenum below the fluidized bed to achieve the reaction temperature. Additional fuel is injected directly into the fluidized bed just above the fluidizing grid to create a reducing zone in which the CaSO_4 reduction occurs. Supplementary air is injected directly into the bed at a higher elevation to create an oxidizing zone. The oxidizing environment at the top of the bed assures high selectivity to CaO , the desired product of the regeneration reaction, by minimizing the formation of CaS , an undesired by-product.

The successful operation of the coupled regeneration/combustor system was demonstrated in a 125 hr uninterrupted run. The mini-plant was operated with limestone sorbent continuously recirculating between the combustor and regenerator until the run was voluntarily terminated. The major purpose of the run was to demonstrate that the system could operate continuously for 100 hours.

During the 100 hours of regeneration, the sorbent underwent about 15 cycles of combustion and regeneration. The average Ca/S ratio during the run was 0.55. This represents about a fourfold reduction in the limestone feed rate which would have been required in a once-through system to control the SO_2 emissions to the average level measured in this run.

The concentration of SO_2 in the regenerator off gas was nearly steady throughout the run and averaged 0.53 mole percent on a dry basis. This is very close to the concentration predicted by a sulfur mass balance based on the feed rate and sulfur content of the coal entering the combustor.

4.3.3.3 Granular Bed Filter Evaluation

The objective of the granular bed filtration program was to determine if such a filter could reduce particulate concentrations in the flue gas, at high temperature and high pressure, to a level which would prevent damage to the gas turbine as well as satisfy environmental requirements.

A number of high temperature runs were attempted but the pressure drop across the filter was extremely high and all attempts at blow-back were unsuccessful. Inspection of the filter elements after each of these runs showed that a hard filter cake had formed on the inlet retaining screens. The filter medium was usually particulate free indicating very little penetration through the screens. The initial tests were made before the preheat burner was installed and it was thought that the plugging was caused by condensation of moisture during start-up. However, runs made after the preheat burner was in operation were also terminated by screen plugging problems. As a result, this filter design was deemed unacceptable for this application.

Operability of a modified filter system was then demonstrated. The end of the initial shakedown phase was signified by the successful completion of a 24 hour demonstration run.

A number of problems were defined during the shakedown and operation of the filter. Demonstrated particulate outlet concentrations are still higher than the tentative gas turbine inlet requirements. Firm turbine requirements have not been set as yet and it may be too early to reach any conclusions regarding the suitability of the filter to protect a gas turbine. The lower outlet particulate loadings of 0.05 gr/SCF meet the current EPA emission standards. In all runs, it was observed that the outlet loadings increased with time. It has not as yet been demonstrated that the EPA emission standard can be met for more than a few hours of operation.

4.3.3.4 Comprehensive Analysis of Emissions

A comprehensive analysis was made of all potentially hazardous materials in the effluents from the mini-plant. Samples of the input and effluent streams were taken and analyzed. This work was performed in cooperation with Battelle Columbus Laboratory. The results of the test are summarized in a report issued jointly by Battelle and Exxon Research and Engineering Company.

A second series of runs were conducted with the regenerator operating. This work was done in cooperation with GCA/Technology Division. The results of the tests will be summarized in a report to be issued jointly by GCA and Exxon.

4.3.3.5 Corrosion and Erosion Materials Testing

The principal objectives of this DOE study is to compile a sound engineering data base for the characterization of the corrosion and erosion lifetime behavior of a number of commercially available alloys when exposed to a pressurized fluidized bed coal combustion environment.

Exxon's program mission is to operate the pressurized fluidized coal combustion mini-plant for 1,100 hours to provide a test site and environment of specimens of potential Westinghouse supplied fireside heat exchanger alloys and General Electric supplied gas turbine materials.

Total exposure time will be 1,000 hours, in 100-hour segments, with the tests interrupted at the 200 and 500 accumulated hour intervals to allow removal, inspection, and re-insertion of the specimens.

The intended mini-plant combustor operating conditons for the exposure runs are nine atmospheres pressure, 1,700 to 1,750°F combustor bed temperature, superficial bed velocity of six ft/sec, and 15 to 20 percent excess air. The coal will be Illinois #6 and the sorbent Tymochtee dolomite. The expected GE turbine section inlet conditions are nine atm, 1,550°F, and 0.72 to 0.92 lb/sec gas mass flow rate.

No additional test work has been funded beyond the corrosion and erosion material testing schedule for completion in the third quarter of 1979. Present plans are to mothball the plant after this date.

4.3.4 Argonne National Laboratory 0.1 Mwt Technology Rig^{65,66}

Argonne National Laboratory (ANL) has been involved in FBC development for over ten years. The original program objectives for the Office of Coal Research consisted of determining: (1) the effect of operating variables at elevated pressures on SO₂ removal, NO suppression, combustion efficiency, additive utilization, solids entrainment, and heat transfer coefficients; (2) the ability of the system to process a variety of coals; (3) the quantity and type of trace-element contaminants in the flue gas; and (4) the kinetics of the reaction between SO₂ and sulfur-accepting additives. Recently, emphasis has been placed on demonstrating and optimizing the sorbent regeneration process and evaluating particulate cleanup and measurement devices. In addition, work is on-going in combustion and synthetic sorbent studies.

The ANL bench scale rig consists of a combustor vessel, coal and additive feeders, a heated compressed air supply, and gas cleanup equipment. Coal and additive is fed pneumatically with peripheral-sealed rotary feeders. Gas is cleaned via two cyclones and subsequently through two filters. The arrangement however is flexible enough to test various cleanup devices. The combustor is constructed of an 11 foot, 6 inch diameter, 316 stainless steel schedule 40 pipe

and is contained within nine foot, 12 inch diameter, 304 stainless steel schedule 10 pipe, with insulating material between the pipes. The six inch pipe is wrapped with resistance heating elements and cooling coils to control the temperature of the bed. Bed cooling is further accomplished by fine hair pin, vertical cooling loops which extend down from the flanged top of the combustor. The coolant is water entrained in air. Fluidizing air inlets, thermocouples, solids feed lines, and solids removal lines are accommodated by the distributor plate. The flue gas is sampled continuously and routinely analyzed for most components. Continuous determinations of NO_x , SO_2 , CH_4 , CO , and O_2 are made. CO_2 is monitored intermittently.

A sorbent regeneration unit initially encountered operational problems due to its small three inch diameter size. It was later reworked by reducing refractory thickness to a 4.25 inch internal diameter. The regenerator was coupled to the PFB combustor, but has since been disengaged due to the limited flexibility offered by the coupled system. Operation of the regenerator unit is a batch process.

During six years of operation, complete parametric tests of combustor operating conditons were made. Originally, the combustor was intended to run in tandem with the regenerator, but they are now run separately.

The greatest limitation of this rig is its small size. The cooling effects of the combustor walls are countered by heating coils, but the effects of the wall on circulation in the bed are significant. The low air throughput of the rig presents difficulty in retaining the heat following the combustor for diagnostic testing. Combustor effluent is cooled by the coils which extend vertically through the combustor, limiting the temperature for diagnostics to less than 600°F . Conversely, its small size is advantageous for flexibility and offers a useful screening device for new concepts.

The ANL program in PFB is a support effort to the DOE program. The flexible rig is suitable as a proving ground for various hot gas cleanup and particulate measurement devices being considered for larger rigs. Regeneration of sorbent is being investigated as a benefit to the entire program, as regeneration can provide an economic benefit to PFBC. A number of additional studies are being conducted to advance this technology.

The six inch combustor has completed parametric testing with various grades of coal and sorbent, and its operating characteristics have been well defined. The sorbent utilization program is continuing as is the diagnostic testing of hot gas cleanup devices. Another six inch diameter rig has been built and is currently operating at atmospheric pressure. It will later be used for hot gas cleanup testing which places the future of the present six inch rig in question.

4.3.5 NASA - Lewis 0.3 MWt Technology Rig^{67,68}

NASA-Lewis, using their own funding, has designed and constructed a combination cylindrical and conical PFB facility for the purpose of obtaining corrosion and erosion rate data with several alloys developed for aeronautical applications. The decision to build a rig to obtain this data was made in 1975, when the lack of this data was observed. In May 1977, the rig was shaken down and logged 138 hours of total running time. The rig has undergone some modifications since then and has logged over 400 hours to date.

The combustor is a combination cone/cylinder, with a 3° taper angle. The lower cylindrical portion is 8.9 inches in diameter and the widest cone diameter is 21 inches. Pressurized air flows through grid plate bubble caps. Temperature and pressure of inlet air can be varied from ambient to 700°F and seven atmospheres, respectively. Coal and dolomite/limestone, mixed prior to injection, enter the bottom of the

combustor via pneumatic feeders. The bed height can be varied by removing solids through any one of the six locations. The bed temperature is maintained by controlling coal flow. Heat is removed by water cooled heat exchangers mounted horizontally in the bed. Products of combustion may be routed either through a cooler, particle separator, and pressure let-down vent or through a diagnostic turbine cascade section, followed by a ceramic filter, gas turbine, and exhaust. The character of the bed surface is monitored by a TV camera mounted in the top of the combustor. Some 180 parameters are monitored, recorded, and reduced to engineering terms by computer.

Small size is the most significant limitation of the rig. It is so small compared to pilot plant size that scale-up information can not be obtained without intermediate rig testing. The combustion design is unique, which adds somewhat to the difficulty of comparing results to other PFB tests.

The very uniqueness of this PFB concept is of value to the entire PFB picture. NASA-Lewis experience with gas turbine technology is also an important asset. Although not currently planned, DOE may contribute funding to this NASA program which is slated to end after the next 400 hour turbine test.

In the first 136 hours of combination tests, all of the NO_x values recorded were below the EPA standard of $0.6 \text{ lb}/10^6 \text{ Btu}$. The average recorder value was approximately half the standard. The maximum observed level of SO_2 was $1.75 \text{ lb}/10^6 \text{ Btu}$, but the average was only 0.63, which is about half the EPA standard of $1.2 \text{ lb}/10^6 \text{ Btu}$. Combustion efficiencies determined by captured solids analysis averaged 99 percent. Measured bed-to-tube heat transfer coefficients varied between 45 and $65 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$, with an average of 55. The small bed size however affects this value. The bed pressure drop is a function of bed weight in this configuration, plus the height, taper angle, and velocity due to the tapered configuration in which some weight is

supported by the reactor walls. Analysis of the solids content of the gases has shown that the conical bed results in less carryover than an equivalent cylindrical bed due to the very low velocity at the surface. Generally, the results of combustion tests in the NASA PFB have duplicated and verified those of other experimenters. Exceptions are those effects related to the conical bed configuration.

More recently, 200 hours of testing have been completed with a rotating turbine. Two 20 hour segments have been run with high inlet particulate loadings of two gr/scf and one 160 hour segment with reduced loadings of 0.2 gr/scf. Excessive erosion was recorded. Pittsburgh coal and Ohio coal similar to that envisioned for the proposed American Electric Power facility have been tested as well as limestone and dolomite. The Ohio coal has a higher carryover rate than the Pittsburgh. The turbine cascade diagnostic section has produced erosion and corrosion data throughout the test period.

Modification of the Aerodyne cyclone has resulted in an improved outlet loading consistently below .05 gr/scf. A ceramic filter was to be installed to reduce loadings even further, but preliminary tests with the filter resulted in a large heat loss, reducing gas temperature below that required for turbine tests. The performance of the ceramic filter is yet to be determined.

Additional characterization of conical fluidized beds should be performed, preferably at higher pressure than the 5.5 atm tested in the NASA rig to date.

Currently, there are plans supported by NASA to begin 400 hours of turbine testing at a projected particulate loading of less than 0.5 gr/scf. DOE funds are sought by NASA to continue the testing beyond 400 hours.

4.3.6 Curtiss-Wright 2.3 Mwt Technology Rig^{59,60}

As part of the 13 MWe PFB pilot plant design effort, a three foot INNER DIAMETER. PFB combustor rig was designed and constructed during Phase I of a five year DOE-funded effort by Curtiss-Wright. The unit was started successfully on July 27, 1977 and has operated over 900 hours on coal to date, though not without problems.

The C-W PFB concept utilizes a seven atmosphere, 1,650°F bed with vertical air cooled heat exchanger tubes. The rig, pilot plant, and conceptual commercial plant are all essentially the same in the vertical dimension, i.e., freeboard height, bed height, tube length, etc. Combustion in the fluidized bed is contained within a five foot diameter (three foot INNER DIAMETER.) refractory lined vessel. Included with the rig are two stages of gas cleanup; and ash removal system; coal and dolomite receiving, storage, transport, and injection systems; computer control and data logging system; on-line gas analysis monitoring and instrumentation; and a small gas (Rover) turbine engine/electric generator. The combustor and heat exchanger are externally supplied with heated shop air exhausting to the atmosphere following combustion, heating, and cleanup. A slipstream with two removeable sections can accommodate a particle analyzer device or turbine cascade. The small gas turbine is located in the slip stream, down stream of the removable section. The turbine will be used for materials and coatings testing and has been run for one hour. Results of turbine testing will be somewhat qualitative, since the blades are very small and not representative of utility sized units. Since the rig operates on auxiliary air, it can operate flexibly to facilitate parametric testing. In addition, the present piping arrangement facilitates changes to cleanup systems and diagnostic devices by replacement of various spool pieces with "T" sections.

The rig is an important element in the PFB program, since it is the largest operating unit. It is supporting the C-W 13 MWe design which is the only pilot plant design sponsored solely by DOE. Results of in-bed and turbine materials tests will be invaluable in assessing the technology.

The 900 hours of testing to date have been devoted to shakedown of the rig and verification of the design parameters chosen for the pilot plant design. Excellent sulfur capture, near design heat and flux, stable operation with good controllability, uniform bed temperature and complete combustion, coal and dolomite feeding, and low NO_x have all been demonstrated in this rig. Hot gas cleanup remains a problem and must be successfully demonstrated to prove this technology. Rotating machinery must also be tested to demonstrate feasibility of turbine operation in the erosive and corrosive environment without deposition and fouling.

The rig is scheduled to begin long term testing in May 1979. Various cyclone configurations will be tried to determine the most effective combination. The Rover gas turbine will also be tested. Material tests of in-bed tubes and heat transfer tests of bare tubes will continue. Plans are to log an additional 500 hours in this test series.

4.4 KEY TECHNICAL ISSUES

4.4.1 Hot Gas Cleanup

The major problem that must be solved to utilize PFB technology is the development of reliable and efficient techniques to remove particulates from the combustion products at high temperature and pressure.

The successful operation of combined cycle PFB power plants requires the removal of particulate particulates from the combustion gases at

they can be reliably used. While some methods and processes are more advanced than others, questions of ultimate efficiency, reliability and equipment life are still unanswered and must be confirmed by both bench scale and pilot scale experiments. Only inertial devices and certain granular bed filters are presently available for pilot plant testing.

The particulate loading limits for acceptable turbine erosion rates are not defined. The estimated limit presently used is 0.002 gr/scf which is more stringent than EPA standards of 0.02 gr/scf for an adiabatic combustor and 0.05 gr/scf for a water or air cooled combustor²⁵. The best performance that two conventional cyclones in series have shown are loadings from 0.15 gr/scf to 0.20 gr/scf with a median particle size of three microns.²⁶ This year testing will be conducted at Exxon with three cyclones in series and at Curtiss-Wright with four cyclones in series. In general, the particle collection efficiency is significantly reduced at high temperature and pressure. A baghouse is the most efficient conventional cleanup device and approaches the proposed turbine requirements at standard conditions. Meeting turbine requirements at temperature and pressure on first generation equipment is unlikely. It will be a major technical achievement to meet even the EPA standards. Turbine conditions will be met by loosening requirements through improved turbine design and by simultaneously improving gas cleanup.

DOE and EPA are sponsoring most of the research in particulate control for PFB combustion. EPRI is sponsoring a test facility capable of testing devices up to 1,800°F. The main thrust of EPRI is development of high efficiency and low energy consumption devices for utility applications. Most of the test work will be performed at temperatures up to 700°F. While test results will provide information which can be utilized for design modifications required for high temperature operation, the work will not be directly applicable on the The Office of Energy, Minerals, and Industry of the EPA has sponsored fluidized

bed combustion for several years. Their aim is to develop and demonstrate new methods for utilizing fossil fuels in an environmentally acceptable manner. The objectives of EPA are to identify potential environmental problem areas and to develop environmental controls, while the fluidized bed combustion technology is still under development. As part of this program, EPA has sponsored several projects in particulate control at high temperature and pressure²⁸.

DOE work in hot gas cleanup has been in support of specific technology rig and pilot plant programs. There has not been a single unified program to develop gas cleaning equipment. The Morgantown Energy Technology Center (METC) has recently been given this responsibility for PFBC and coal gasification. METC has formed a task force which is reviewing the potential applications and advantages of hot gas cleanup and assessing the research needed to support the development of this technology²⁹.

The research work to date has been primarily concerned with determining process feasibility and in developing equipment. Correlations of performance and analytically defining collection mechanisms has received little attention. The main reason is the absence of high temperature and pressure sampling equipment. This equipment is now becoming available and more effort is needed to develop a basic understanding of high temperature and pressure collection mechanisms.

4.4.1.1 EPA Project Characterizations

- High Temperature, High Pressure Particulate Control with Ceramic Bag Filters³⁰ (Aerotherm Division/Acurex Corporation).

Bench-scale research indicates fine particle control at high temperature and pressure can be achieved using barrier filtration

with ceramic bag filters. Accelerated media cleaning tests at high temperatures and pressures show that several ceramic filter structures are capable of surviving in excess of 50,000 cleaning pulses while maintaining pressure drop at acceptable levels. Tests also indicate that high filter media face velocity (air-to-cloth ratio) operation will be possible for a high temperature - high pressure (HTHP) filter system. To accomplish operation at high air-to-cloth ratios will require special cleaning techniques. High filter velocity operation is a desirable objective because smaller, less expensive particle control equipment will result.

- Particulate Control in PFB Combustion - Granular Bed Filter Application³¹ (Exxon Research and Engineering). Exxon installed a Ducon granular bed filter in their mini-plant for checkout and testing. Initial tests were terminated due to screen plugging causing excessive pressure drops and preventing blow back cleaning. The filter was redesigned with the inlet screens removed and more freeboard to prevent entrainment of the filter media during blow back. Operability of the modified filter was demonstrated. However, in all runs the outlet loadings increased with time. EPA emission standards could only be met for a few hours at a time.
- High temperature, High Pressure Gas Cleaning and Particle Removal Equipment Test Facility³² (Westinghouse Research Laboratory). Westinghouse, with the support of both the Department of Energy and the Environmental Protection Agency, has designed, constructed, and operated a test facility for evaluating particle removal equipment at temperatures up to 1,600°F and pressures up to 15 atm. Hot gas flows up to 12 lb/sec can be provided. Equipment up to 4.5 ft in diameter and eight ft in length can be mounted within an insulated pressure shell for testing. A number

of particle removal devices have been tested including cyclones, granular bed filters and porous ceramic filters.

- Development of High Temperature, High Pressure Electrostatic Precipitators³³ (Cottrell Environmental Sciences, Inc.). The objective of this project was to demonstrate the technical feasibility of electrostatic precipitation at temperatures to 2,000°F and pressures to 500 psig. Technical feasibility is the ability to generate a stable corona over the range of temperature and pressure indicated. This was accomplished in a laboratory scale tubular precipitator with no-flow, particle-free operation. This method was chosen to provide a well controlled, economical evaluation of the electrical characteristics of the system over the total range of variables. A second phase program is need to carry the work further to evaluation of particulate collection characteristics.

The work has demonstrated a stable corona over the entire range of temperature and pressure required by the emerging fluidized bed combustion and coal gasification applications. The work indicates that conditions for electrostatic precipitation are more favorable as temperature and pressure increase.

4.4.1.2 DOE Project Descriptions

- Program Research and Development Announcement (PRDA RA01-79ET15055). Exploratory Research Development, Testing and Evaluation of Systems or Devices for Hot Gas Cleanup, Issuance Date: April 4, 1979.³⁴ DOE desires to develop and demonstrate hardware-oriented prototype systems or devices for cleanup of high temperature, high pressure gases in pressurized fluidized bed combustors for use with open cycle turbines in the utility and industrial sectors. Contaminants of interest include particulates, alkali, halogens, and trace metals.

Their solicitation is divided into two categories:

- Category 1 -- Concept Definition, Laboratory and Bench Scale Testing, and Evaluation (estimated duration - two and one-half years)
- Category 2 -- Process Design Testing and Verification (Estimated duration - three and one-half years)

It is anticipated that multiple contracts will be awarded for both categories.

- Granular Bed Filter³⁵ (Combustion Power Company). The Combustion Power Company, under EPA sponsorship, designed a moving bed granular filter for use with their CPU-400 pilot plant. As design of the filter progressed, ERDA-sponsored a program to convert the system to use coal. The moving bed filter was constructed in November 1975. During the first system heat up to 1,300°F, the inner panel of the filter buckled due to excessive stress. After an ERDA review, a more gradual and lower risk development program was initiated. A series of performance evaluations are now being carried out under low pressure conditions on hot and cold models. The objective of these tests is to establish a reliable filtration correlation.

The 1,000 hour hot flow performance test began in May 1979. A decision to design and construct a 16 atm, 1,800 acfm test facility will be made after a review of these tests.

- Hot Gas Cleanup and Separation³⁶ (Mechanical Technology, Inc.). A new concept, called a Cyclocentrifuge, was involved during an analytical study in which the desirable characteristics of the cyclone and the centrifuge were combined. A cold flow model of

11 scfm was built and tested at ambient conditions. A nearly 100 percent collection efficiency was obtained for three micron particles at a pressure drop of three psi. Hot and pressurized tests are planned for this year at the METC gasifier.

- Particulate Analysis Instrumentation for FBC Systems³⁷ (Leeds and Northrup Company). The objectives of the L&N program are to design and construct a prototype instrument for measuring particulate loading and particle size distribution in high temperature gas streams and to evaluate the instrument on PFB combustion systems. The technique has been used in narrow angle light scattering. The instrument has been assembled and was installed and tested at Argonne National Laboratory. Further tests are planned at the Curtiss-Wright facility.
- In Situ Laser Measurements in Coal Processing Systems³⁸ (Spectron Development Laboratories, Inc. - SDL). The objectives of this program are to test the capability of an SDL particle Morphokinometer and to obtain particle size and velocity measurements in the output train of the ANL fluidized bed combustor. Testing has been completed. Additional tests are planned at the Curtiss-Wright Small Gas Turbine facility.

4.4.2 Turbine Development^{69,70,71}

Turbines in a PFBC combined cycle system will be subjected to erosive and corrosive conditions not currently experienced in commercial operation. Commercial turbines supplying power to Fluid Catalytic Cracking Units (FCCU) can withstand erosive loadings three to four times that expected in a PFBC system, but there is no associated corrosive atmosphere, and the temperature is lower. The FCCU turbine designs have improved to the point where continuous service between rebuilds of three years or more is common. It is likely that a

conservative turbine design using proper materials could withstand the erosive environment of a PFB system, however, the corrosive atmosphere complicates the problem.

These corrosive elements in the PFB effluent are primarily certain salts, specifically sodium and potassium sulfates, which deposit on the blade surface. If vanadium and lead are present, the corrosive properties are magnified. Sodium concentrations in gas turbine distillate fuels are typically one ppm, which corresponds to 0.02 ppm in the combustion gas in the turbine. Experimental results from the CURL rig show a discharge of sodium of two ppm or two orders of magnitude higher. Traditional high strength nickel base turbine materials will not be suitable in this type of application without special coatings.

The problem is selecting an appropriate material to withstand both corrosion and erosion and incorporating this material into a conservatively designed turbine with appropriate maintainability and/or blade protection features.

A segment of the turbine development program is contained within each of the technology rig programs. Cascade tests have been run since the CURL rig and a significant amount of data is being generated in "static" testing. Dynamic tests, have taken place to a more limited degree. The static and dynamic turbine material testing programs are described below:

4.4.2.1 Static Turbine Material Tests

Coal Utilization Research Laboratories

Early tests at the Coal Utilization Research Laboratories indicated that fouling of blades is a problem at combustion temperatures over 1,700°. A cascade section consisting of a nozzle guide valve segment

from a Rolls-Royce "Proteus" marine gas turbine was located downstream of a PFBC.

Gas flow into the cascade was about Mach 1 at 1,600°F. The cascade was a cobalt base alloy, X40. Two sample rods were arranged at 90° to the flow axis at a point downstream of the cascade where the flow was about Mach 0.6. One of the rods was a nickel base alloy and Nimonic 75; The other was a high-chromium nickel-base alloy EPK 55, designed for corrosion resistance. Four tests totaling 204 hours of operation were carried out. Two levels of bed temperature (1,650°F and 1,750°F) were explored. The resultant cascade inlet temperatures ranged from 1,565 to 1,675°F, and outlet temperatures ranged from 1,520 to 1,650°F. There were several temperature excursions due to coal feed problems where the bed temperatures approached 1,800°F.

In general, there was no significant deposition on the cascade at a bed temperature of 1,650°F. At 1,750°F, the deposits were extensive. The deposits were subsequently removed by blasting with nutshells. The quantity of dust passing through the cascade was about 250 ppm. The size of the dust particles as determined by Coulter count, was typically 95 percent less than 10 microns and 85 percent less than five microns. Test results show that greater than 97 percent of the alkali was retained in solid form.

The two nickel-base alloy target rods, Nimonic 75 and EPK 55, the X40 nozzle and flyash from the second cyclone were submitted to the General Electric Gas Turbine Division for evaluation. The following conclusions were made:

- Significant hot corrosion attack was evident on the Nimonic 75 (exposure time more than 200 hours) and X40 (exposure time 200 hours) material (See Figure 4).

- Oxidation of the type that is a precursor to hot corrosion was evident on the EPK 55 alloy (exposure time 200 hours).
- Erosive attack by gas stream particles was very slight to nonexistent.
- The test particles were soft and friable and appeared to be different than those from high-temperature coal combustion.

Coal Research Establishment

Tests of candidate turbine materials were subjected to the exhaust of an AFBC at the Coal Research Establishment (CRE). The principal function of the test was to study the corrosion of in-bed and above-bed heat exchanger materials. The combusting gases were also exhausted through sections containing test pins of gas turbine materials. Gas velocities were 100 ft/sec in the first section, 200 ft/sec in the second section, and 100 ft/sec in the third section. The gas temperatures in the first two sections were 1,472°F and 1,328°F in the third section. The turbine specimens were exposed for 2,000 hours. The flue gas contained some 0.25 gr/SCF (450 ppm) dust and 350 ppm SO₂. The combined Na and K alkali metal content in the form of aerosols was close to two ppm and the chlorine content of the coal was 0.04 percent. The alloys IN671 and a Pt/A coating on FSX 414 suffered very little attack. Sulfidation was observed on the IN671 sample and also on the U-500, Hastelloy X, and Inconel 617. The investigators considered the conditions had been severe enough to produce corrosion in the test period.

Combustion Power Company

CPC has carried out a program of testing in a four atmosphere fluidized bed combustor coupled to a direct fired turbine, and a smaller

2.2 square foot atmospheric model fluid bed combustor. This testing, begun in March 1975, has been directed toward the accumulation of data with regard to hot corrosion in the coal combustion process and the development of methods for dealing with it.

Material specimens are placed in the freeboard of the atmospheric combustor. Exposure temperatures varied between 1,600 and 1,700°F, and included temperature excursions up to 1,780°F. Testing has been conducted with Illinois #6 coal and Kaiser dolomite. Attempts at measuring the alkali content of the gas in the freeboard have yielded estimates of two ppm of Na.

After 2,000 hours of testing in the one atmosphere combustor, very little corrosion was observed. The results did not distinguish between 304 SS and IN-738 or IN-713C. The corrosion resistance of IN-738 is vastly superior to 304 SS or IN-713C in conventional hot corrosion tests. A series of preliminary short duration tests showed that significant hot corrosion attack did occur if the temperature in the freeboard exceeded 1,700°F. The CPC tests did show evidence that the addition of an aluminosilicate additive to the bed suppresses the release of alkali sulfate with a reduction in the potential for hot corrosion.

The main conclusion from the CPC work is that temperature is the single most important factor in determining whether hot corrosion will occur in an atmospheric coal combustor system. At temperatures of 1,600°F, hot corrosion did not occur, while temperature excursions above 1,700°F produced significant corrosion.

Exxon

Exxon Research and Engineering Co. (ERE) is operating the mini-plant as part of a DOE program and includes tests involving turbine and heat

exchanger materials. The turbine materials, housed in a cascade section, are supplied by General Electric, and configured with vaves and blades to be of similar dynamic design as an operating turbine.

The typical miniplant combustor operating conditions for the exposure runs are nine atmospheres, 1,700 to 1,750⁰F bed temperature, six ft/sec superficial velocity, and 15 to 20 percent excess air, with an inlet temperature the cascade of 1,550⁰F.

The shakedown phase is completed. Turbine blade materials were exposed to pressurized fluidized bed coal combustion conditions for 17 and 100 hours. The airfoil-shaped U-700 turbine specimens experienced a regular pattern of fly ash deposition. These specimens were returned to GE for selective metallurgical examination. Reports on several of the blade specimens indicate some signs of erosion at the leading edge and signs of very localized incipient corrosion near the leading edge on one or two specimens. In these tests, the measured particulate concentration was 0.05 to 0.06 grain/SCF and the particle size distribution showed 80 percent less than 10 mm with a mean particle size of six mm.

The extended exposure tests of the heat exchanger materials and turbine blade materials started in June 1978 with a continuous 250 hour run segment. Test conditions were steady and in the proper control range; flow of flue gas through the turbine test section on specification at nine atm and 1,500 - 1,600⁰F temperature. Combustor temperatures were maintained at 1,725⁰F. The combustor consumed approximately 6,000 lbs/day of coal and 1,700 lb/day of dolomite. Particulate measurements taken during the test yielded loadings of 0.03 to .05 grains/SCF. After the test, seven of the heat exchanger specimens and three of the turbine blade specimens were intentionally removed for meallurgical analysis.

Specimens of the U700 alloy from the 100 hour shakedown test were examined in detail and showed sulfidation, erosion, and deposition processes occurring simultaneously near the specimen leading edge. This suggests the presence of alkali vapor of about one to 10 ppm concentration. Specimens removed after the 1,000 hour test are being evaluated.

Turbine materials and cladding materials have been tested to date; vapor deposited coating tests are planned for the next test series.

NASA-Lewis

Turbine cascade tests have been conducted at the NASA-Lewis facility. Four candidate materials have been exposed to the PFB effluent in the initial test series, IN-100 (a corrosion susceptible alloy), IN-792, U-700, and MM-S09. Specimens are located in a carousel wedge which spins at 550 rpm to simulate a turbine and vary particle impingement angles.

The test specimens suffered damage from corrosion and erosion the extent of which was more dependent upon test conditions than material properties. The rate of damage was extreme in 10,000 hours and unacceptable for application in a turbine.

Additional "carousel" tests have been made with much lower input particulate loadings, but published information is not yet available.

4.4.2.2 Dynamic Turbine Tests

Dynamic turbine testing has taken place in only two PFBC facilities, NASA-Lewis and Curtiss-Wright. Dynamic testing is considered to be a spinning turbine and not a rotating carousel as in the NASA-Lewis rig.

NASA-Lewis

NASA-Lewis has been experimenting with turbine-related technology in PFBC. Three rotating turbine tests have been conducted to date with one remaining test planned. Two runs of 20 hours each with 2 gr/SCF loading, and a third of 160 hours and 0.2 gr/SCF loading have all resulted in excessive erosion. The cyclones have been improved, reducing loadings to 0.05 gr/SCF, and a 400 hour test with this loading has probably commenced, but results have not been reported. Following the 400 hour test, funding will expire, and the program will end.

Curtiss-Wright

A small (one pps) Rover turbine will be run for 1,000 hours in a slipstream of the SGT/PFB technology rig. To date, approximately six hours have been accumulated during shakedown operations. Mechanical problems unrelated to the PFBC itself on the turbine have set back this program. However, the 1,000 hours should be completed by late September 1979.

4.4.3 Coal Feeding^{72,73,74,75}

Although a coal feeding program has not been initiated directly as a part of the DOE PFBC program, there is research ongoing which is applicable and may be integrated at a later date. Currently, DOE PFBC test installations are equipped exclusively with Petrocarb feeding devices which split and meter coal flow to the coal nozzles. The Petrocarb is a dense-phase transport system which accepts coal from a pressurized lock hopper to a weigh cell and a splitter system. From the splitter system, a coal is transported pneumatically through a number of feed lines to the combustor. Many problems have been encountered and are envisioned with this system, including coal line plugging, coal distribution, and coal metering. Coal in pneumatic

transport is highly erosive, promoting wear on transport pipes and feed guns. There are three methods of feeding being investigated under DOE contract and a fourth being considered. "Feeding" in these programs does not include injection into the combustor or gasifier, but to components between the injector and the coal crushing units. The purpose, then, is to pressurize, distribute, and meter the coal to the injectors being developed as part of individual programs.

The objective in each program is to find alternates to lock hopper and slurry systems. Lock hopper systems are cumbersome and require frequent maintenance of valves. Slurry systems adversely affect the energy balance because of the thermal inefficiency introduced by the vaporization of the liquid.

The DOE-sponsored concepts will be described briefly. The devices being developed are in the prototype stage and have not, as yet, been installed on an actual combustion device. The program is centered on gasifier development, but should also find application in the PFBC programs.

4.4.3.1 Lockheed Missiles and Space Company, Inc.

Lockheed has focused upon the kinetic extruder, a device which uses kinetic energy to distribute coal evenly. Coal flows down a pipe under pressure and is fed into a rotating disc shaped chamber with slots at the periphery. Coal flows out the slots, propelled by kinetic energy imparted by the rotation of the disc. Flow is controlled by the geometry of the mechanisms and the speed of the rotating disc. Phase I, Selection of Concepts and Phase II Laboratory Scale Feeder Development are complete and Phase III, Feeder Evaluation, in progress.

4.4.3.2 Ingersoll-Rand Research, Incorporated

Ingersoll-Rand has concentrated efforts on a screw feeder and a piston feeder. The screw feeder consists of a feed section, sealing section (screw, barrel), a device to break plugs as they are issued from the barrel, and a receiver. The barrel is heated to provide sealing with plasticized coal. Experiments were conducted with varying barrel heat and different screw configurations. The piston configuration chosen from three variations is the single action piston feeder and utilizes two coaxial delivery pistons which are in turn actuated by drive pistons activated by a pneumatic or hydraulic power supply. Two pistons form a cavity which is filled with coal in one position and discharges the coal in a second position. The pistons close together, displace the gas into the system, and then return to the original position.

4.4.3.3 Foster-Miller Associates, Inc.

Foster-Miller is developing two coal feeding devices, the linear pocket feeder (LPF) and the centrifugal feeder. These two concepts were chosen from four concepts developed in Phase I. The LPF is essentially an enclosed tubular conveyor with very tight clearance. It has five sections: the feed section, the sealing section, the unloading section, the gas transfer section, and the return section. Coal is fed to the conveyor at atmospheric pressure and pressurized in the sealing section. The coal is then dropped, as the conveyor moves into a pressurized vessel for feeding to the combustor, and the air pocket is displaced by pressurized water.

The centrifugal feeder is similar to the kinetic extruder concept developed by Lockheed and discussed above. The device operates in a continuous mode, seals with moving coal, transports by centrifugal force, and meters by controlling the rotational speed of the feeder head.

4.4.3.4 Conspray, Inc.

Conspray is developing a dry powder pump derived from a concrete pumping device. Concrete is very abrasive and similar in pumping requirements to coal. The particles are fluidized in a hopper-like device, while a cylindrical enclosure is brought across and sealed from the hopper. The coal trapped by the enclosure is ejected by a piston and metered by the frequency of ejections. Testing of a prototype at Pittsburgh Energy Research Center is planned for the near future.

SECTION 5.0
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